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PEDIATRIC CARDIAC ARREST AT A LARGE ACADEMIC CHILDREN'S HOSPITAL

RESUSCITATION PERFORMANCE, QUALITY IMPROVEMENT, and ASSOCIATIONS WITH RETURN OF SPONTANEOUS CIRCULATION

BY

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ABSTRACT

Introduction

Cardiac arrest is a significant public health problem. For pediatric patients, years of potential life lost are difficult to comprehend and long-term survival, despite a rise in recent years, is abysmal. With the introduction of new technologies that allow for the measurement of the quality of cardiopulmonary resuscitation (CPR), it is possible to study factors associated with survival, that until now have remained elusive for the pediatric population. In 2013, a data-driven pediatric resuscitation quality improvement (QI) initiative was implemented at the Johns Hopkins Charlotte R. Bloomberg Children's Center. Based largely on experience during that program's implementation, this dissertation examines approaches to assessing resuscitation quality, surveillance of in-hospital pediatric cardiac arrest, and patient, event, and performance factors associated with acute survival.

Methods

This work commences with a comprehensive review of the literature from 2004-2010 examining methods and metrics reported for the measurement and assessment of resuscitation quality. The next manuscript describes the design, development and deployment of a surveillance system used to detect pediatric cardiac arrests. The events identified by this system were then included in the QI initiative, the results of which are the focus of the third manuscript. This manuscript characterizes cardiac arrest and resuscitation quality over the 2013-2015 period explores associations between resuscitation quality and return of spontaneous circulation (ROSC).

Results

This work reveals variability in how resuscitation quality is defined, measured, and analyzed. By leveraging hospital information technology and medical device data, identification of

pediatric cardiac arrest can be improved with an associated increased capture in the proportion of objective quality data used by QI efforts. Lastly, it demonstrates that resuscitation performance over time can be improved and evaluation of performance using novel methods provides previously unobtainable insight regarding factors that influence survival.

Conclusions

These results show that resuscitation quality can be defined and measured in a myriad of ways and this understanding can focus QI initiatives in novel ways. These initial findings suggest there is tremendous opportunity, in further exploration of device-derived resuscitation quality data, performance patterns, and patient characteristics and their interactions, to drive precision-medicine interventions during pediatric cardiac arrest.

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CHAPTER 1
THESIS OVERVIEW

Cardiac arrest is a significant public health problem. For pediatric patients, years of potential life lost are difficult to comprehend and long-term survival, despite a rise in recent years, is abysmal. With the introduction of new technologies that allow for the measurement of the quality of cardiopulmonary resuscitation (CPR), it is possible to study factors associated with survival, that until now have remained elusive for the pediatric population. In 2013, a data-driven pediatric resuscitation quality improvement (QI) initiative was implemented at the Johns Hopkins Charlotte R. Bloomberg Children's Center. Based largely on experience during that program's implementation, this dissertation examines approaches to assessing resuscitation quality, surveillance of in-hospital pediatric cardiac arrest, and patient, event, and performance factors associated with acute survival.

This work commences with a comprehensive review of the literature from 2004-2010 examining methods and metrics reported for the measurement and assessment of resuscitation quality. The next manuscript describes the design, development and deployment of a surveillance system used to detect pediatric cardiac arrests. The events identified by this system were then included in the QI initiative, the results of which are the focus of the third manuscript. This manuscript characterizes cardiac arrest and resuscitation quality over the 2013-2015 period explores associations between resuscitation quality and return of spontaneous circulation (ROSC).

Manuscript One: Comprehensive review of reported quality of CPR metrics from the release of the 2004 Utstein recommendations through the release of the 2010 AHA Emergency Cardiovascular Care Guidelines.

This comprehensive review demonstrated that although guidelines for performance during resuscitation exist, there is wide variability in how those guidelines have been interpreted with respect to defining metrics used for both real-time feedback and post-event assessment. Over the period under review there was an almost complete inversion in the proportion of published studies using human and animal data and those that use simulation-based data, with increasingly availability over time of simulation-based systems capable of measuring CPR performance. While improvements in both clinical-device and simulation-based technology have enabled ease-of-access to resuscitation performance data, the measures used and their interpretation are largely driven by the manufacturer; most reports focused on chest compression depth and rate and their measures of central tendency and infrequently assessed these against some performance target. The results of this work demonstrate that despite expert consensus publications, professional organization guidelines, and data availability there is perhaps even more heterogeneity now than before in reporting, paradoxically, homogeneity in performance measurement. More investigation of standard definitions and reporting of resuscitation quality measures should be considered.

Manuscript Two: Design, Development and Deployment of a Pediatric Cardiac Arrest Surveillance System.

The objective of this work was to describe the use of an active cardiac arrest surveillance system that leverages automatically generated clinical event notification data, identifies all pediatric cardiac arrests, and facilitates collection of physiologic and performance data for use in post-resuscitation review and event debriefing. This system was developed in 2012 and deployed on January 1, 2013 to support the implementation of a pediatric resuscitation quality improvement (QI) initiative within the Johns Hopkins Children's Center. Over the period there was an increase in detected events for the entire pediatric population anually and in previously under-reported clinical areas. As a function of increased cardiac arrest event detection, the capture of resuscitation quality and patient physiology data used during debriefing also increased. As a result of review of this data during debriefing the reliability and accuracy of patient and event data included for submission to the national resuscitation registry that this institution participates in. More work is needed to collect appropriate denominator data for all areas within the Children's Center where cardiac arrest events take place in order to determine incidence or events. It may be possible to datamine electronic health records (EHR) to identify if any cardiac arrest events were not detected, and inform performance improvements to the surveillance aspects of the system.

Manuscript Three: 1625 Minutes of Pediatric Cardiac Arrest: Analysis of Resuscitation Quality Performance and Acute Survival in a Large Academic Medical Center: 2013-2015.

This manuscript reports, in detail, patient, cardiac arrest, and resuscitation quality characteristics for events during which pediatric patients in the Children's Center experienced a resuscitation. Events included for this analysis were those that had quantitative resuscitation quality performance data captured using an organizationally standardized "smart defibrillator" and collected as part of the QI initiative. For this work, custom software was developed by the candidate, that used raw data from these defibrillators to generate novel performance metrics not available as part of the manufacturer's basic data review application. These measures along with demographic and epidemiologic variables were analyzed across years, and between those that did or did not experience return of spontaneous circulation (ROSC). These analyses were used to inform the development of a logistic regression model. The results for this study show that during the QI period, quality did improve when evaluating performance using minute epochs. When comparing in-hospital cardiac arrest patients who survived to those who did not, performance was comparable across most measures. Chest compression depth, rate and chest compression fraction were generally compliant using AHA guidelines. There were differences in the number and duration of interruptions. The adjusted odds of survival were significantly increased per increase in number of interruptions greater than 10 seconds. These results seem to suggest that regardless of whether or not chest compressions are performed at AHA guidelines the number of interruptions and their duration begin to play important roles in achieving ROSC and ultimately survival. This work has provided an innovative set of measures with which to characterize and analyze chest compression and interruption-related resuscitation quality. Further novel work is needed to explore "interruption modes" and their interactions with other factors with an aim toward discovery of how they may be influencing survival.

CHAPTER 2
A COMPREHENSIVE REVIEW OF REPORTED QUALITY OF CPR METRICS FROM THE RELEASE OF THE 2004 UTSTEIN RECOMMENDATIONS THROUGH THE RELEASE OF THE 2010 AHA EMERGENCY CARDIOVASCULAR CARE GUIDELINES

INTRODUCTION

In 2004 the Utstein recommendations for uniform reporting practices for resuscitation quality improvement and research were updated (Jacobs 2004). This update built on previous Utstein statements and aimed to simplify reporting best-practices, unify terminology used during in- and out-of-hospital cardiac arrest, as well as, within adult and pediatric populations, and to differentiate between essential and desirable data for quality improvement and research efforts (Zaritsky 1995, Cummins 2007, Cummins 2004). The 2004 statement specifically discussed use of data for quality improvement and epidemiologic registries, recognized data collection forms and tools, as well as an acknowledgement of (and solutions for) "problems with data definition, collection, linkage, confidentiality, management, and registry implementation" (Jacobs 2004). These guidelines focus heavily on patient demographic information, cardiac arrest characteristics (such as duration and rhythm), medication administration, and survival outcomes. They, however, provide little guidance regarding standardization of measures describing quality of CPR despite the clear relationship between such elements and survival (White 1998, Losert 2006). Though not in their stated scope, these recommendations also do not help to address the same lack of standards in CPR studies undertaken in the animal or simulation lab, both of which provide the ability to expand or refine current methods of making these measurements.

Emergence of technology that allows for advanced measurement of both provider performance and patient condition has become more ubiquitous (Scholten 2011, Cheng 2015, Fischer 2011, Martin 2013). Increased monitoring in both intensive and general care areas allows for increased capture of patient physiology before, during, and after cardiac arrest and smart defibrillators allow for precise measurement of chest compression characteristics such as depth, rate, and recoil velocity. Important basic science and animal experimentation has investigated perfusion and physiologic markers of cardiac output. New methods of performance analysis have become popular, and guidelines for basic and advanced CPR recommendations have been released every 5 years, informing practice and influencing what has been reported and in what form (AHA 2005, AHA 2010). This multifactorial shift in the techno-medical landscape of CPR research, training, and clinical practice may have influenced deviations and variability in CPR quality measures.

This review aims to characterize the evolution of reported metrics of CPR quality measures and their data sources in the period between the publication of the 2004 Utstein recommendations and the release of the 2010 AHA guidelines and to lay the groundwork for a call to action for a new expert consensus reporting of resuscitation quality measures.

METHODS

Search Strategy

With review by and recommendation from a medical librarian experienced in performance of systematic reviews a search strategy was developed to identify all publications (published 2004 through 2010) reporting measures of CPR performance quality (Appendix 1). Five literature databases were searched (Medline, CINAHL, Cochrane Health Technology Assessments, Cochrane Reviews, and Cochrane Trials). The search strategies for each database are listed in Appendix 1. Inclusion criteria were: all (human, animal, simulation) original research (RCT, Observational Studies, etc), with metrics that described internal (physiologic) or external (related to chest compression attributes or psychomotor-based) markers of CPR performance and were written in English or had an English translation available.

Study Selection

100% of Medline titles and abstracts were screened for eligibility by at least two reviewers [BE, MB, AM, JDA]. These reviewers evaluated a random sample of 25 articles from the returned results, consulting the Title and Abstract review protocol (Appendix 2) to ensure selection process comprehension and compliance agreement; once 100% agreement was achieved Medline title and abstract review commenced. During selection of articles for full-text review, disagreements were decided by a third reviewer [EAH]. Search results from CINAHL were then de-duplicated against the 2-person reviewed Medline results, unique CINAHL titles and abstracts were reviewed for consideration for full-text review. Results from the Cochrane Library (Controlled Trials (CT), Health Technology Assessments (HTA), Cochrane Reviews (CR)) were de-duplicated against the Medline/CINAHL list of articles considered for full-text review; all of the unique Cochrane articles were considered for full-text review. All articles considered for full-text review were then evaluated for inclusion [JDA]. Data were extracted from all articles meeting the inclusion criteria.

Data Extraction

A data extraction form (Appendix 3) was developed which included Publication Date, Title, Database Accession Number, Journal, Authors List, Resuscitation Model Studied (Human, Animal, Simulation), Location, Quality Assessment Device, and Resuscitation Duration of Analysis. Studies were extracted in ascending order by publication date (most distant to most recent). When previously unidentified measures were detected they were added as new columns and their data extracted. If a measure was encountered that had previously been identified its presence was noted in the corresponding column. Data extraction was conducted by a single reviewer [JDA].

Data Analysis

Analysis included summary of studies included, CPR quality assessment devices and techniques reported, resuscitation models used, journal and geographic distributions, and characterization of: defibrillation, interruption, physiologic and chest compression-related quality measures, and the evolution of chest compression-related quality measures over the period.

RESULTS

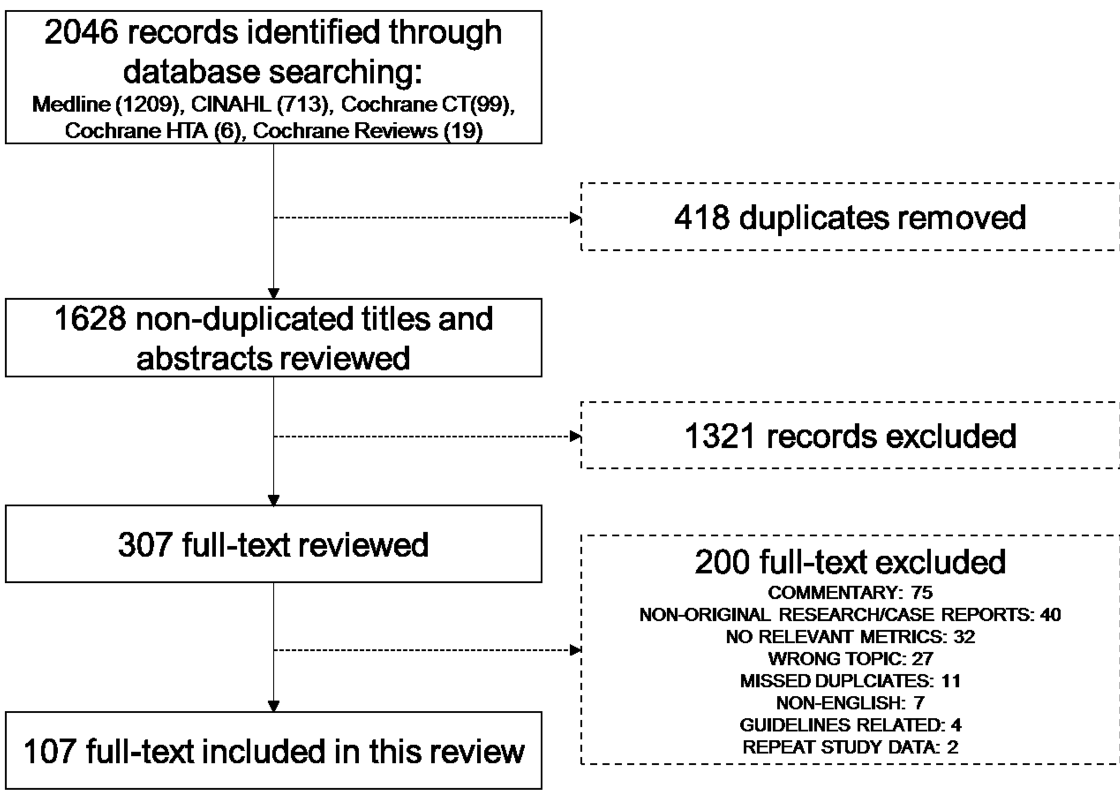

Figure 1. PRISMA flow chart of study selection.

Search Strategy

The search of the 5 databases yielded 2,046 records (Medline: 1,209, CINAHL: 713, Cochrane CT:99, Cochrane HTA: 6, Cochrane Reviews: 19), of those 1,628 were unique. Of the 1,209 Medline titles and abstract that underwent a 2-person review, the percent agreement was 89% (1090/1209). Both reviewers selected 154 articles for full-text review. The reviewers disagreed on 139 articles which went to the third reviewer; 43 of these were ultimately selected for full-text review. Fifty of the 360 CINAHL records were selected for full-text review. After deduplication 38/99 (CT), 4/6 (HTA) and 17/19 (19) of the Cochrane articles were selected for full-text review. A total of 306 articles underwent a full-text review and 35% (n=108) were included for data extraction (Figure 1).

Included Studies	
Resuscitation Model	n=108
Simulation	57 (53%)
Human	37 (35%)
Animal	14 (13%)
Studies Reporting more than one Model	n=3
Human+Animal	2 (2%)
Human+Simulation	1 (1%)
Animal+Simulation	0 (0%)
Animal+Simulation+Human	0 (0%)
Quality Assessment Technique	
Number Reported	n=112
Simulator	45 (42%)
Defibrillator-Based	33 (31%)
Clinical/Lab Instrumentation	20 (19%)
Video Review	6 (6%)
Custom Device	4 (4%)
Live-Time Human	4 (4%)
Quality Measures	
Number Reported	n=166
Chest Compression-related	78 (73%)
Interruption-related	48 (45%)
Physiologic-related	23 (25%)
Defibrillation-related	17 (16%)
Duration	
Number Reported	n=44
Percent of Studies Reporting Duration	41%
Duration - m*inutes*	
Median (IQR)	5 (3-6.25)
Minimum	1
Maximum	30
Evaluated Quality in Epochs	
Number Reported	n=16
Percent of Studies Reporting Epochs	15%
Epoch Duration - *seconds*	
Median (IQR)	60 (30-60)
Minimum	20
Maximum	120

Table 1. Summary of studies included in the review (n=108). (Multiple types reported)

Included Studies

Over the period the majority of studies used simulation as a model for studying resuscitation quality. Fifty-three percent of studies used simulation compared to 35% and 13% of human or animal models respectively. Only 2 studies reported observations made from data derived from human and animal measurements; only 1 study reported data from human and simulation based observations. Most studies reported only one type of method for measuring quality elements (i.e. "Quality Assessment Technique") of interest; five reported 2 methods (e.g. a live-time human and video review). 42% of studies used data obtained from simulators, 31% from defibrillator-based devices, 19% from clinical monitoring (i.e. bedside monitors attached to human subjects) or clinical monitors attached to instrumented animals, the 10% were split amongst video-review or live-time human evaluation and the remaining 4 percent used custom devices developed by the investigators expressly for the study. The vast majority of studies reported quality measures related to the performance of chest compressions (78%), about half characterized interruptions to CPR (45%) or physiologic responses during CPR (43%), and only 16% reported measures related to defibrillation. Only 41% of studies reported the duration of resuscitation; of those the median duration was 5 minutes (IQR: 3-6.25); the maximum duration was 30 minutes. Even fewer studies reported the evaluation of quality during time slices or "epochs" of the overall duration. Of the 16 studies (15%) that did report quality as measured and aggregated over individual epochs, the median epoch period was 60 seconds (IQR: 30-60s) (Table 1).

Publications by Journal, Year, and Location

Approximately 75% of articles were published in just 3 journals: Resuscitation (58%), Critical Care Medicine (10%), and Circulation (6%), with Resuscitation publishing almost 4 times as many of the articles in Critical Care Medicine and Circulation combined. The remaining studies were published in 21 journals representing primarily intensive/critical care, emergency medicine, and anesthesia-related disciplines (Table 2). Over the six-year period, the number of articles by year showed a steady though small increase of approximately 3%, with an overall 3-fold increase from 2004 to 2010 (Table 3). Including multiple location, there were 23 unique study locations. The largest concentration (40%) were carried out in the United States, with 1%-8% across different countries; no studies conducted were reported to have taken place in Africa or South America (Table 4).

JOURNALS (n=24)	n (%)
RESUSCITATION	62 (58%)
CRIT CARE MED	11 (10%)
CIRCULATION	6 (6%)
JAMA	3 (3%)
RESPIR CARE	2 (2%)
J EMERG MED	1 (1%)
AM J EMERG MED	2 (2%)
ANN EMERG MED	2 (2%)
INTENSIVE CARE MEDICINE	2 (2%)
ACTA ANAESTHESIOLOGICA SCANDINAVICA	2 (2%)
PEDIATR CRIT CARE MED	1 (1%)
PREHOSP EMERG CARE	1 (1%)
CRIT CARE	1 (1%)
CHEST	1 (1%)
PEDIATRICS	1 (1%)
INT EMERG NURS	1 (1%)
ANESTHESIOLOGY	1 (1%)
N ENGL J MED	1 (1%)
EMERG MED J	1 (1%)
WIENER KLINISCHE WOCHENSCHRIFT	1 (1%)
BMC EMERGENCY MEDICINE	1 (1%)
SCANDINAVIANJOURNAL OF TRAUMA, RESUSCITATION, AND EMERGENCY MEDICINE	1 (1%)
NURSING EDUCATION PERSPECTIVES	1 (1%)
ANAESTHESIST	1 (1%)

Table 2. Frequency of publications by Journal

YEAR	n (%)
2004	7 (7%)
2005	11 (10%)
2006	15 (14%)
2007	14 (13%)
2008	18 (17%)
2009	21 (20%)
2010	21 (20%)

Table 3. Frequency of publications by Year

LOCATION (n=24)	n (%)
USA	43 (40%)
NORWAY	9 (8%)
UK	7 (7%)
GERMANY	5 (5%)
AUSTRIA	6 (6%)
MULTICOUNTRY	6 (6%)
TAIWAN	5 (5%)
AUSTRALIA	3 (3%)
JAPAN	3 (3%)
FINLAND	2 (2%)
CHINA	2 (2%)
FRANCE	2 (2%)
DENMARK	2 (2%)
SWITZERLAND	2 (2%)
SLOVENIA	1 (1%)
KOREA	1 (1%)
SINGAPORE	1 (1%)
SWEEDEN	1 (1%)
CANADA	1 (1%)
NEW ZEALAND	1 (1%)
NETHERLANDS	1 (1%)
IRAN	1 (1%)
IRELAND	1 (1%)
BELGIUM	1 (1%)

Table 4. Frequency of publications by Location

CPR Quality Measurement over time

Six techniques/devices were used to measure CPR quality across the four defined categories (defibrillation, interruption, physiologic, and chest compression-related). Simulator, defibrillator, and clinical-monitor based systems were the most prevalent (Figure 2). While clinical/lab instrumentation makes up almost 1/5 of all devices, their use is relatively equally spread across all years, whereas for simulators and defibrillator-based techniques there is in an increase in frequency and concentration of use as each year progresses. (Figure 3).

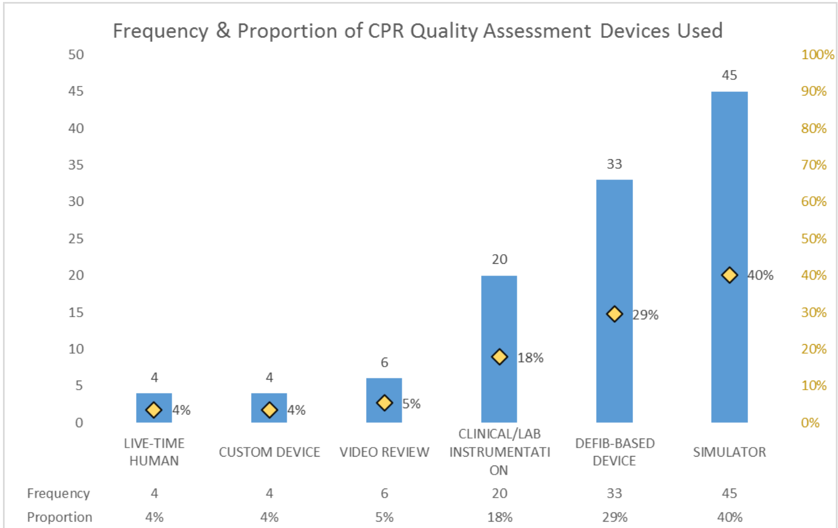

Figure 2. Frequency and proportion of CPR quality assessment devices used

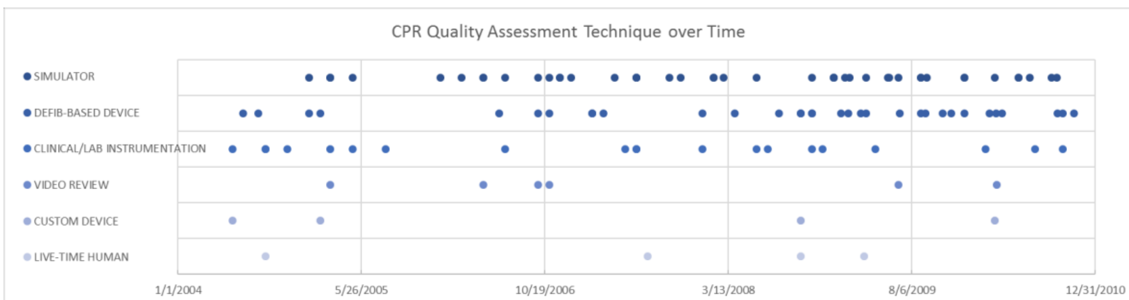

Figure 3. Distribution of CPR quality assessment devices over time

Resuscitation Model Type over time

Over the six-year period the percent of studies using simulation models went from 0% to 62% with a corresponding 2.5-3.0 factor decline in human and animal studies over the period (Figure 4). This shift was most prominent from 2004 to 2006 for simulation studies and from 2004 to 2008 for human and animal studies.

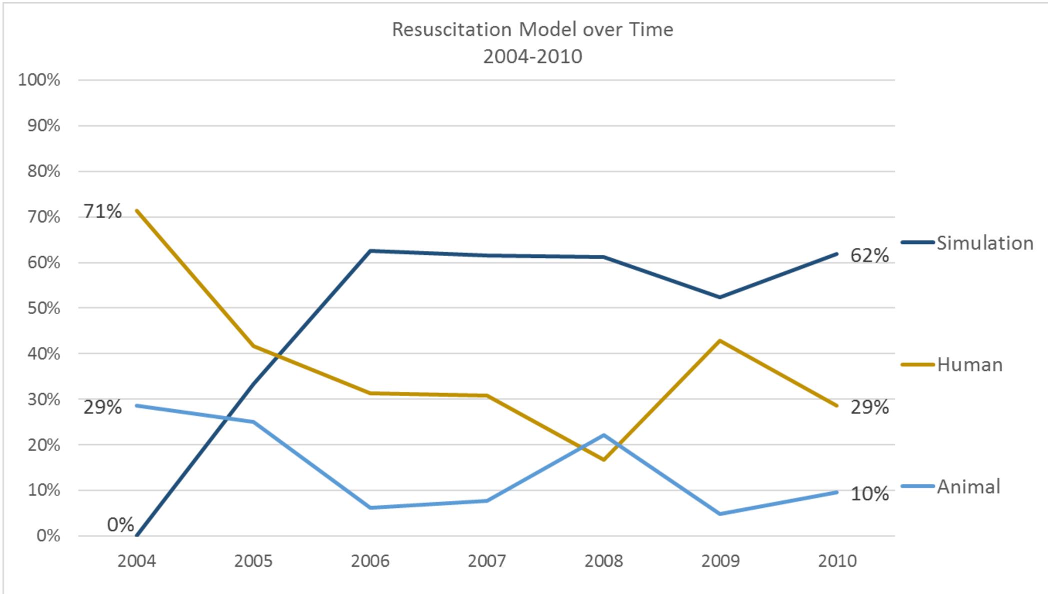

Figure 4. Studies using simulation, human or animal models and their change over time.

Defibrillation-related quality measures

Of the 17 studies that reported quality measures related to defibrillation, five distinct measures were reported; time to defibrillation, pre-shock pause, post-shock pause, defibrillator pad placement, and shock appropriateness. Of the nine time-to-defibrillation measures most only report the time from some initial event to defibrillation. These initial events are non-standardized and range from "time to first shock" (Wollard 2006) to "beginning of BLS to First AED shock" (Roessler 2009), and three studies reported results that were before or after some threshold amount of time ([Stiell 2004: ≤8 Minutes]; [Hunt, 2009: ≤ 3 minutes]; [Mhyre 2010: < 2 minutes). Two studies mention quality as "early" or "delayed" but provided no objective quantifiable threshold; only Stiell in 2010 provides a threshold and a qualifier i.e. "more than 2 minutes from the time of pulselessness to defibrillation" was considered "delayed". Two studies reported correct defibrillator pad placement (Wollard 2006; Nishiyama 2008) and one reported percent of appropriate shocks delivered (Weidman 2010). Fourteen studies discussed pre (n=9) or post(n=5)-shock pause, with the first mention occurring in

2008 by Edelsen et al. They characterized the pre-shock duration in bins of 10 seconds from the time of chest compression cessation to defibrillation and reported success of defibrillation and its association with each bin. Two months later, in November 2008, Shah et al. made the first report of post-shock duration. In 2010 Sell reported “optimal” pre and post-shock durations (which they called “pre and post-defibrillation pauses”) based on ROC analysis of human derived data from a defibrillator based assessment device. This group suggested the optimal pre and post-defibrillation pauses to be <3 seconds and <6 seconds respectively (Sell 2010).

Interruption-related quality measures

Forty-eight studies reported a quality measure related to interruptions in chest compressions. Over the period, the majority (n=37) of these measures are related to the concept of non-performance of chest compressions when they actually should be performed. These metrics were varied and calculated differently. Early in the period, reference to “hands-off” was popular with the absolute measure and proportion of time chest compression were not being peformed were reported. This concept transitioned to being referred to as “no-flow” in 2008; Roessler (2009) was the first to discuss and to emphasize “no-flow” as appropriate for human-derived data and “hands-off” as more appropriate for simulation-derived data, distinguishing between the two by definition of blood flow (though perhaps the simulators experienced no-flow of electrons from their sensors during periods of non-chest compression). In September of 2009, Christenson further redefined the concept in terms of its inverse, and reported this measure as “chest compression fraction” defined “as the proportion of resuscitation time without spontaneous circulation during which chest compressions were administered”. The negatively connoted measure names remained prevalent through the rest of the period, though in 2010 two similar positive descriptions, “CPR hands-on time ratio” (Jost 2010) and "compressions fraction" (Rea 2010) were coined. No studies reporting a conceptually equivalent measure offered a definition for objective assessment of its quality. Several studies (n=11) reported interruptions, measured multiple ways, but only one reported a target for maximum interruption duration tolerable, stated as "no longer than 30 seconds" (Ko 2005) however offers no guidance on tolerable frequency of these interruptions. In terms of identifying an interruption, only 9 of the 48 studies provided a definition or methodological approach for determining what non-compression periods qualified as an interruption. Effestol in 2004 began counting a pause in compressions as an interruption after 5 seconds, and Abella et al. in 2005 set this threshold at 4 seconds, reporting that a sensitivity analysis setting the threshold from 2-5 seconds did not alter their results. Later, beginning in 2009, this threshold decreased with seven studies starting the interruption clock after 2 seconds had passed. Four of the studies started counting non-compression time as an interruption after 1.5 seconds (Yang 2009; Sutton 2009; Nesset 2010, Ong 2010). Sutton et al also considered periods of chest compressions with a chest compression rate < 40 also as interruption time. Ong and Hunziker (Hunziker 2009; Ong 2010) did not consider pauses in chest compressions due to ventilation as interruption time if the ventilation duration was less than 10 seconds.

Physiology measures over time

Measurements made evaluating the association between CPR quality and the physiologic response of the subject occurred in 23 (22%) of the studies. Metric use did not vary greatly over the period in terms of novel measurements appearing and then gaining popularity. The most common physiologic markers used were coronary perfusion pressure (n=14) and end-tidal carbon dioxide (n=13); the least common, each with only a single mention, were brain oxygen tension, continuous cardiac output, mean intrathoracic pressure. On average animal studies reported 3 times as many metrics as did those using human subjects (ANIMAL: 4.5

vs. HUMAN 1.5). There appeared to be oscillating periods of publication of human then animal studies approximately every other year, with no apparent trends associating year with number of studies in either category or across both.

Author	Year	Human	Animal	CORONARY PERFUSION PRESSURE	END-TIDAL CARBON DIOXIDE	ARTERIAL BLOOD PRESSURE (Systolic and Diastolic)	CEREBRAL PERFUSION PRESSURE	OXYGEN SATURATION	MEAN ARTERIAL PRESSURE	INTRA-CRANIAL PRESSURE	COMMON CAROTID BLOOD FLOW	HEART RATE	CEREBRAL OXIMETRY	BRAIN OXYGEN TENSION	CONTINUOUS CARDIAC OUTPUT	MEAN INTRATHORACIC PRESSURE	# OF MEASURES
Newman	2004	X											□				1
Aufderheide	2004	X		□	□			□								□	4
Timerman	2004	X		□													1
Castillo	2004	X		□	□												2
Yannopoulos	2005		X	□			□										2
Yannopoulos	2005		X	□	□	□	□		□	□	□	□					8
Yannopoulos	2005		X	□	□	□	□	□	□	□							7
Yannopoulos	2006		X	□	□	□	□		□	□	□	□					8
Bertrand	2006	X						□									1
Larsen	2007	X				□											1
Mally	2007	X					□										1
Krep	2007	X			□												1
Ristagno	2007		X	□	□												2
Lurie	2008		X		□	□		□	□	□	□			□			7
Li	2008		X	□	□												2
Aufderheide	2008		X	□		□	□			□	□						5
Pargett	2008		X		□												1
Havel	2008	X		□	□												2
Wu	2009		X	□	□	□		□	□			□			□		7
Maher	2009	X				□											1
Li	2010		X	□													1
Solevag	2010		X	□				□	□				□				4
Axelsson	2010	X			□												1
				14	13	8	6	6	6	5	4	3	2	1	1	1	

Figure 5. Physiology measures and their frequency over time by study and measure type.

Chest compression quality measures evolution

Quality of chest compressions was assessed and reported in a wide variety of ways that can be categorized as: 1) Time to initiation, 2) rate, 3) depth, 4) recoil, 5) multifactorial (a combination of the other measures performed satisfactorily) and 6) ergonomically (hand placement, body mechanics, use of performance enhancing adjuncts).

Initiation: Twelve studies (Rittenberger 2006, Roessler 2007, Dias 2007, Nishiyama 2008, Brown 2008, Bolle 2009, Iwami 2009, Hunt 2009, Yang 2009, Hunziker 2010, Merchant 2010) reported time to starting compressions. An equal number identified "first compression" (singular n=5) or "first compressions" (plural n=5), as the threshold for making the measurement, and two identified time to first CPR intervention, which include chest compression along with other techniques including ventilation and defibrillation. All (12/12) reported a time measurement (seconds or fractional minutes), none (0/12) reported a threshold for success e.g. time to start less than "X" seconds, and report of definition of time zero was variable with only one study reporting a well-defined definition of the period "collapse to first CPR" (Iwami 2009).

Rate: Most studies report a measure of central tendency most often characterized as actual compressions / minute, some studies would account for non-compression time (eg time to ventilate) and deduct this from the denominator, while others would report an average of instantaneous rates. These were equally variable in the name ascribed to the measurement ranging from compression rate, compression frequency, cc/min, cpm to name a few. Until Jantti in 2009, studies reported the average rate and if assessed for quality determined if the average rate was compliant either above a lower threshold or between a lower and upper threshold. Jantti et al reported percent of compressions at an "Adequate" rate defined as 90-110 compressions per minute as measured by a simulation-based assessment device. Of the 53 studies reporting on rate, only Havel in 2010 reported the percentage of compressions within a range defining quality; this study also was simulation-based and used the same assessment device as Jantti. Seventeen studies made assessments of rate quality based on lower and/or upper ranges, one reported "per reviewer's assessment", one "per ILCOR guidelines", and one as a function of coronary perfusion pressures. Of those that quantified quality, 6 reported goal compressions per minute of 90-110, four reported ~100, and the remaining were variable with some defining inadequate as rates less than 50, and the widest range of adequacy defined as 80-120 compressions per minute.

Depth: Depth was similarly variable in terms of making and reporting measurements, and specifying thresholds that defined quality. Of studies reporting depth, 30% reported percentages of all compressions falling within lower and/or upper thresholds defining quality. During the period, Perkins et al, in 2005 first reported depth quality in terms of percentages “shallow” or percentages “excessive”. The studies that followed in reporting were inconsistent in terms of the thresholds, the units, and whether or not quality was reported as compliant (i.e percent within the limits) or non-compliant (i.e percent above and/or below upper and lower limits respectively). Thirty-five studies quantified quality this way (as compliant or non-compliant), with 89% reporting percentages of compressions as falling *within* upper and lower bounds, while not specifying what percentages that were too shallow or too deep. Eighteen studies identified depth quality as “sufficient”, “adequate”, “correct”, or “incorrect” and the most frequently defined range for quality was $\geq$ 38 and < 51mm. Only three studies provided direct reference to a published recommendation or guideline (JAPANESE, ILCOR, AHA) (Nishiyama 2010, Noordergraaf 2006, Dias 2007) as an evidence base for setting upper and lower limits for assessment of depth quality.

Recoil, Multifactorial, & Ergonomics

Of the 100 studies that reported chest compression quality measures, 26% of these studies provided data on chest-wall recoil. There was significant variability in both naming and definition with 16 studies referring to chest recoil as “release”, four as “recoil”, and three as “leaning”. Of the 26 studies that reported recoil, 22 (85%) were simulation-based studies using the simulator as the assessment device, with the rules for assessment being determined by the simulator itself. Twenty-two studies reported a quality assessment comprised of performing two or more measures in compliance as defined by the study (e.g meeting performance goals for depth and rate and recoil in order to be considered compliant); for example Maisch (Maisch 2009) described this as: “"incorrect compressions" incorrect compressions could be due to one or more simultaneous errors, for example, the wrong hand position and too-deep chest compression”. Twenty-two studies reported correct-hand placement, (14 of these overlapped with those reporting recoil and also relied on sensors in the simulator to determine correct placement). Hunziker in 2010 was the only study to report "correct" body mechanics in terms of arms and shoulders in correct position, and Perkins in 2006 is the only study to report time to placement of a backboard, though it makes no mention of a threshold for defining quality (i.e. how long is too long to place a backboard).

DISCUSSION

In 2015, the Institute of Medicine published a report on sudden cardiac arrest highlighting variability in survival across cities and institutions, and missed opportunities for saving lives (Graham 2015). As one of the mechanisms for addressing this issue, they called for standardized and required reporting of cardiac arrest events. However, they did not suggest any specific metrics or mechanisms for capturing these data. This is likely because there was significant heterogeneity in reporting outcome measures in regards to how quality of cardiopulmonary resuscitation is defined. There is not a clear gold standard set of metrics for CPR quality. On review of the original manuscript describing chest compressions in 1960, Kouwenhoven, Knickerbocker and Jude reported demographics of the subjects and survival outcome metrics, but did not describe the quality of CPR delivered (Kouwenhoven 1960). Of note, they do give an overarching description of the manner in which they performed CPR as *"Firm pressure is applied vertically downward about 60 times per minute. At the end of each pressure stroke the hands are lifted slightly to permit full expansion of the chest. The operator should be so positioned that he can use his body weight in applying the pressure. Sufficient pressure should be used to move the sternum 3 or 4 cm. toward the vertebral column."* This focus on key factors of depth, rate, recoil and minimizing pauses was important but did not provide a mechanism for capturing or reporting the quality of resuscitation performance on humans.

In the 1990's, leaders of the resuscitation research community recognized that disparity in reporting practices was likely to limit the ability to compare or aggregate data in any meaningful way. For instance, survival was reported variably as survival to hospital admission, to 24 hours, to hospital discharge, etc… Similarly, characteristics of the resuscitation such as bystander CPR, initial rhythm, etc… were variably reported. The first Utstein Consensus Guidelines in 1995 were developed in an effort to create consistency in the elements and the details of how the elements were reported (Zaritsky 1995) However, these were still focused on demographic pre-arrest variables and post-arrest outcomes and there was still very little information in regards to the quality of the resuscitation; the 2004 recommendations were the first set attempting to address that issue. Of note, in January 2005 two seminal papers were published with data on quality of CPR captured with new technology that represented a seminal shift towards describing and defining intra-arrest quality data (Abella 2005a, Abella 2005b).

Shortly afterwards, in 2007 Kramer-Johansen et al published "the results from an international consensus working group to propose common definitions and criteria for reporting variables of CPR quality, based on the best available data for the importance of various CPR variables." (Kramer-Johansen 2007). This work focused on developing recommendations for collection and analysis of data based on these definitions for quality improvement initiatives, clinical trials, and research. This tiered approach attempted to address realities of data availability and resolution based on study design, however, it ultimately introduced a lack of uniformity in how some variables are reported. For instance, they suggested setting the average and standard deviation as the minimum requirement for analysis of compression depth, but then went on to say "investigators could also" report the fraction of minutes with a depth less than a minimum threshold (<38mm) This implied additional calculations to be made at the minute level, but did not provide guidance regarding the definition to define time zero of the first minute (on which all other minutes are derived).

They continued to further expand the recommendation by suggesting that the epochs could even be less than a minute "(30s intervals or less)" while not addressing the lack of uniformity suggested by this recommendation. They also failed to mention the potential benefit in terms of increased sample size. This example serves not to point out these inconsistencies but truly highlights challenges in developing a comprehensive yet flexible set of variable definitions that allow for the both insight as well as exploration. Kramer-Johansen et al provided excellent recommendations for depth, recoil, duty cycle, rate, interruptions, ventilation, and devices during CPR; however their discussion on adjuncts is limited and offer little guidance on reporting their use. Despite this important work, there were few studies published in the years following this publication that follow these recommendations fully.

Analyses conducted using simulator or defibrillator-based quality assessments largely are defined by and calculated using manufacturer derived output. In many respects this can be viewed positively in that it provides investigators with tools to make their research efficient and reliable. However, it may limit the way in which performance, and thus quality, may be evaluated. In terms of uniform reporting, homogeneity is desirable but not if these measures do not provide a resolution of detail sufficient to drive improvement. For example, an average chest compression depth that hides periods of excessively inadequate depth to create coronary perfusion pressures, is *not* desirable, and possibly misleading. One might be misled by the ready-made graphs and statistics provided by the manufacturer applications. At a minimum these potential pitfalls need to be highlighted boldly both by industry producers of such tools, as well as by researchers and educators using them to determine an individual or team's performance during a resuscitation, regardless if the patient's life-giving flow is driven by blood or electrons. As reported earlier, 30% of studies described quality of chest compression depth in terms of the percentage of compliant compressions but compliance was defined differently by each study. It can be argued that this is an improved way to evaluate performance rather than looking at the average depth of compressions out of all compressions performed as was reported in 45% of studies in this review. However even this approach may suggest good compliance, while hiding potentially devastatingly poor performance. As an example, if 80% of compressions were quality compliant using guidelines for depth driven by lower and upper targets, then one might be tempted to conclude, and report that compression depth was "good". However, if the 20% of non-quality compressions occurred sequentially in the first 5 minutes of an arrest then the consequences for a favorable neurological outcome are likely significant!

CONCLUSION

Unfortunately, this review demonstrates that despite four Utstein conferences and the Kramer-Johansen consensus document, there is perhaps even more variability now than before in regards to reporting of quality CPR metrics. Simultaneously an emerging trend toward a limited set of available metrics from device manufacturers creates a barrier to access of raw data for use by QI analysts, educators, and researchers striving to standardize data elements for inclusion in large registry-based studies. Given the fast-paced and ever-changing technology and research landscape, this heterogeneity in reporting and homogeneity in data availability will only become more unwieldy, requiring active resolution before the IOM's goals of standardization can be realized. Continuation of this work by way of an expert consensus meeting of resuscitation stakeholders to redefine reporting of resuscitation quality measures should be considered.

APPENDIX 1 – Search Strategies

PUBMED SEARCH STRATEGY

Date Run: 10/31/16

((((("Cardiopulmonary Resuscitation"[Mesh]OR "cardiopulmonary resuscitation" [all fields] OR ("cardiopulmonary" [all fields] AND "resuscitation" [all fields] OR "CPR" [all fields] OR "PALS"[all fields] OR "pediatric advanced life support" [all fields] OR "paediatric advanced life support" [all fields] OR "Code Blue" [all fields] OR "Mouth-to-Mouth Resuscitation" [all fields] OR "Mouth-to-Mouth Resuscitations" [all fields] OR "Basic Cardiac Life Support" [all fields] OR "BLS" [all fields]))

AND (((("Outcome Assessment (Health Care)"[Mesh:NoExp]) OR "Treatment Outcome"[Mesh]) OR "Guideline Adherence"[Mesh]) OR "Patient Outcome Assessment"[Mesh] OR (("patient outcome"[tiab] OR Blood pressure[mesh] OR blood pressure[tiab] OR arterial pressure[tiab] OR end-tidal carbon dioxide[tiab] OR physiologic*[tiab]) AND (assessment[tiab] OR quality[tiab] OR depth[tiab] OR rate[tiab]))))))

COCHRANE SEARCH STRATEGY

Search Name:
Date Run: 10/05/16 20:22:39.312
Description:

ID	Search	Hits
#1	MeSH descriptor: [Cardiopulmonary Resuscitation] explode all trees	766
#2	CPR or "Cardio-Pulmonary Resuscitation" or "Code Blue" or "Mouth-to-Mouth Resuscitation" or "Basic Cardiac Life Support" or BCLS or "pediatric advanced life support" or PALS or "paediatric advanced life support"	1259
#3	#1 or #2	1603
#4	MeSH descriptor: [Quality Assurance, Health Care] explode all trees	3860
#5	MeSH descriptor: [Patient Outcome Assessment] explode all trees	121
#6	MeSH descriptor: [Outcome Assessment (Health Care)] this term only	6014
#7	MeSH descriptor: [Guideline Adherence] explode all trees	886
#8	quality	108972
#9	#4 or #5 or #6 or #7 or #8	114915
#10	#3 and #9	526

CINAHL SEARCH STRATEGY

Date Run: 10/3/16

Search	Limiters/Expanders	Last Run via	Results

S4 S2 AND S3 Search modes - Boolean/Phrase Interface - EBSCOhost Research Databases; Search Screen - Advanced Search; Database - CINAHL Plus with Full Text 1,823

S3 ((MH "Outcome Assessment") OR (MH "Treatment Outcomes+") OR (MH "Guideline Adherence")) OR ((("patient outcome" OR blood pressure OR arterial pressure OR end-tidal carbon dioxide OR physiologic*) AND (assessment OR quality OR depth OR rate))) Search modes - Boolean/Phrase Interface - EBSCOhost Research Databases 298,645
Search Screen - Advanced Search
Database - CINAHL Plus with Full Text

S2 (MH "Resuscitation, Cardiopulmonary+") OR ((cardiopulmonary AND resuscitation)) OR (CPR OR PALS OR "pediatric advanced life support" OR "paediatric advanced life support" OR "Code Blue" OR "Mouth-to-Mouth Resuscitation" OR "Mouth-to-Mouth Resuscitations" OR "Basic Cardiac Life Support" OR BLS) Search modes - Boolean/Phrase Interface - EBSCOhost Research Databases 13,620
Search Screen - Advanced Search
Database - CINAHL Plus with Full Text

S1 (MH "Resuscitation, Cardiopulmonary+") Search modes - Boolean/Phrase Interface - EBSCOhost Research Databases 10,206
Search Screen - Advanced Search
Database - CINAHL Plus with Full Text

APPENDIX 2 – Title and Abstract Review Protocol

DEFINITIONS

SURVIVAL OUTCOMES

ACUTE, TO DISCHARGE, NEUROLOGICALLY INTACT, ALIVE AT 6 MONTHS, ETC

NON-TECHNICAL SKILLS

TEAMWORK, COMMUNICATION, LEADERSHIP, MANAGEMENT

COGNITIVE/VIRTUAL

KNOWLEDGE TESTS, MULTIPLE CHOICE, COMPUTER-BASED ONLY

PCAC

POST CARDIAC ARREST CARE MEASURES: O2, TEMP, ETC

DECISION ALGORITHM

Is a resuscitation-related study?
If NO > Exclude: Other
IF YES
Does have Internal (physiology, anatomy, etc mesaures eg blood pressure, etco2, nirs) or External (measureable observations eg. depth, rate, time to defibrillation, visual chest recoil)
IF YES > Full Review Internal or Full Review External or "X" both
IF NO > Exclude one or more: SURVIVAL, NON-TECHNICAL, COGNITIVE, PCAC

IF NON-ENGLISH > EXCLUDE: NON-ENGLISH

APPENDIX 3 – Data Abstraction Form Elements

```
Publication Date - Epub If available – From Database
YEAR – Extracted from Publication Date
Title – From Database
Accession – From Database
Full Text Available – Y|N
Author      - From Database
CPR ANALYSIS DEVICE – Free Text
LIVE-TIME HUMAN – Y|N
VIDEO REVIEW – Y|N
SIMULATOR – Y|N
DEFIB-BASED DEVICE – Y|N
CUSTOM DEVICE – Y|N
CLINICAL/LAB INSTRUMENTATION – Y|N
LOCATION – Free Text
ANIMAL – Y|N
SIM – Y|N
HUMAN – Y|N
No Relevant Data – Y|N
Non-English – Y|N
```

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CHAPTER 3
DESIGN, DEVELOPMENT AND DEPLOYMENT OF A PEDIATRIC CARDIAC ARREST SURVEILLANCE SYSTEM

BACKGROUND AND SIGNIFICANCE

Cardiac arrest (CA) is one of the world's deadliest medical conditions as well as a significant public health challenge. The most recent estimates suggest that in the United States approximately 500,000 adults and children suffer a cardiac arrest annually; globally the number is in the millions. In the U.S. survival from cardiac arrest is <15% (Nichol 2008, Go 2013, Merchant 2011, Chan 2010, Morrison 2013) resulting in approximately the same number of deaths as colorectal, cancer, and prostate cancer, influenza, pneumonia, auto accidents, HIV, firearms, and house fires combined (CDC 2013). Though less common in children than adults, pediatric sudden cardiac arrest incidence, case-fatality, and lost opportunity is not insignificant.

Literature published at the turn of the century suggests that pediatric cardiac arrests occur in 0.7% to 3% of pediatric hospital admissions and 1.8% to 5.5% of pediatric intensive care unit (PICU) admissions (Reis 2002, Slonim 1997, Suominen 2000, Ronco 1995). Nation-wide 4,000 pediatric in-hospital cardiac arrests (IHCA) per year *require at least two minutes* of cardiopulmonary resuscitation (Bembea 2010). In the PICU estimates suggest at least one cardiac arrest per 100 admissions;(deMos 2006). Recent estimates suggest the number of annual PICU admissions is between 230,000 and 410,000, resulting in a possible annual range of cardiac arrests from 2,300 to 4,100 in PICUs in the U.S. (Randolph 2004, Garber 2003).

Pediatric in-patients are increasingly monitored by a variety of electronic sensors, along with regular and frequent interaction by a range of providers throughout the course of their care. Despite this high-degree of electronic and human monitoring, when an IHCA occurs, awareness of the event may be limited to those involved. Individuals who are distant from the event, whether it be geographically (the other side of the unit/building), temporally (the next day), or institutionally (another department), may be unaware that the event even occurred.

At the Johns Hopkins Children's Center, measurement of the incidence of "true cardiac arrests" was a perpetual and particularly refractory challenge and accurate statistics were essentially non-existent. Despite Electronic Health Record (EHR) documentation, participation in a large cardiac arrest and resuscitation registry, dedicated resources to abstract and enter data, internal emergency response teams, bedside monitors and "code blue" buttons, surveillance of these events was passive, and as a result, limited.

Identification of cardiac arrest events usually took place when the Pediatric Rapid Response Team (RRT) was called. At this point the event was documented on a paper and eventually physically handed to the organizational group responsible for event accounting. Pediatric cardiac arrest is rare and potentially more so in general care settings (Girotra 2013). These events occur less frequently on the wards versus the Emergency Department, ICU, OR and MRI procedures areas. In these areas the RRT is seldom activated, and thus the identification mechanism never is triggered. This reduces the likelihood that these acute and critical care area events will be detected, documented, and discussed as part of evidence-based quality improvement initiatives. In order for all events to be captured, an active and reliable surveillance system is needed.

In April 2012 this institution's entire pediatric population was moved into a new clinical building. Despite the advanced technology present in the building, including integrated nurse call, code blue button, and electronic paging systems, there was no increase in detection of CA events. These systems, among others, were not being leveraged to serve as notification sources of possible cardiac arrest for use as part of an active surveillance system. As a result, valuable data captured by advanced bedside monitors and smart defibrillators (those that display and record patient and performance data during a resuscitation) were not being collected or evaluated, and ultimately not being used to benefit providers or future patients.

This loss of data and under-identification of pediatric cardiac arrest events represents significant missed opportunities for learning, performance improvement, and contribution to a larger body of scientific knowledge. These opportunities align directly with the National Academies' 2015 recommendations as described in "Strategies to Improve Cardiac Arrest Survival" including the need for comprehensive surveillance, the need for robust data collection and dissemination, and improving the delivery of high-quality resuscitation (Graham 2015).

OBJECTIVE

To describe the development of an active cardiac arrest surveillance system that leverages automatically generated event notification data, identifies all pediatric cardiac arrests, and facilitates collection of physiologic and performance data for use in post-resuscitation review and event debriefing.

METHODS AND MATERIALS

Process Flow: Resuscitation Event Analysis Clearinghouse (REACH) Surveillance System

Existing information systems utilized on the medical campus, and specifically, at the onset of cardiac arrest were identified as surveillance notification data sources. These systems were configured to automatically message the surveillance system software application known by the acronym "REACH" (*Resuscitation Event Analysis Clearinghouse)* each time they are activated, providing information regarding date, time, and location of "event." The system is purposefully broad in attempting to capture any *possible* pediatric cardiac arrest (defined as a child who received chest compressions and/or defibrillation), prioritizing sensitivity over specificity. As notifications are added to the system, "software was written to screen the message by a combination of factors including geographic origin and message text; these are iteratively refined in order to automatically differentiate as potentially a pediatric event versus definitely an adult event. Pediatric notifications are then automatically disseminated to a multi-disciplinary quality improvement (MDQI) group via email as a "potential cardiac arrest". The flow to this point is fully automated, standardized, and requires no human intervention. The manual part of the process begins as notifications are received by the MDQI group and determination of cardiac arrest status takes place. When verification occurs that a true cardiac arrest has occurred, these events are designated as such in REACH and data collection of bedside monitor and smart defibrillator data is initiated. Notification, event and physiologic and performance data are analyzed and made available for review through different organizational mechanisms.

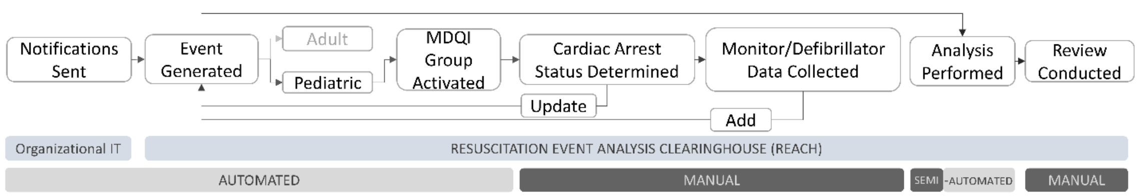

Figure 1. Conceptual Model of Pediatric Cardiac Arrest Surveillance System Process flow.

Design: Surveillance System Components

A. *Organizational IT Systems*: used at the onset or during cardiac arrest and capable of sending email messages. The ability of every system identified to send email messages in the peri-arrest period largely drove the design decision to leverage email as the messaging protocol for notifications.
B. *Organizational Enterprise Email*: receives messages from Organizational IT systems (#1). Based on sender, flags messages as valid for consumption by polling service (#6). Uses rule-based processing to identify likely pediatric-related notifications. Relays pediatric notifications to MDQI listserv (#5).
C. *Relational Database*: stores the following: user, notification, event, resuscitation, and various rules, preference, and usage data.
C1. Automatic full back up every 24 hours and differential backup every 1 hour.
D. *System Logic and User Interface*: provides management of notification, event, and monitor/smart defibrillator records and data analysis features.
E. *Listserv*: includes the members of the MDQI group. This list is the primary method by which cardiac arrest status communicated amongst the group once determined.

F. *Polling Service*: queries the Organizational E-mail (#2), retrieves and extracts new notification message data, standardizes and inserts in database (#3).

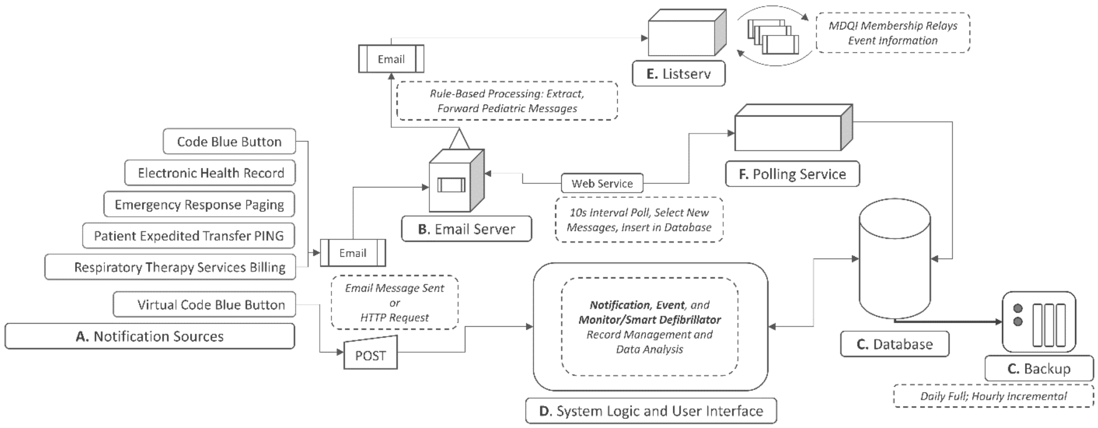

Figure 2. Pediatric Cardiac Arrest Surveillance System Data flow.

Development: Notification Sources

The following describes what configuration or development was need to integrate each notification source into the REACH system.

PING (Johns Hopkins, Baltimore) - This organizationally developed web-based messaging service is used to communicate throughout the Children's Center and was harnessed for two particular classes of events that had the potential to represent a cardiac arrest. Integration of this system was achieved by the list owners (clinicians) adding the REACH email address to the recipient list for the following situations involving critically ill children:

- PET (Pediatric Expedited Transfer) - When a critically ill child needs an expedited transfer from the Emergency Department to the PICU a the PET team is paged.

Code Blue Button - Connexall (Connexall USA Inc. Boulder, CO). The intended use of these buttons is to summon additional help for care providers during urgent or emergency situations. When used in conjunction with a clinical telephony solution (Ascom North America. Morrisville, NC), this system allows for text-based messaging to groups of care team members through integrated call systems, clinical phones, or email. Integration was achieved by (the clinical engineer department) adding a rule that triggers an email to the REACH account when buttons are pressed.

Emergency Response Paging - SDC Intellidesk (SDC Solutions. Manchester, NH.) When the Pediatric Rapid Response Team (RRT) is called for and dispatched (at this institution for both cardiac arrest and non-cardiac arrest emergencies) a message is sent via page to members of the team. The paging system can also send a copy via email. Integration was achieved by (the pager administration office) adding the REACH email address to the RRT recipient list.

Electronic Health Record (EHR) - Sunrise Clinical Manager (Allscripts. Chicago, IL). This EHR has the capability to trigger an email when cardiac arrest or rapid response flowsheets are opened and used to document the event. Integration was achieved by (a Clinical Information System technical lead) adding a rule defining the REACH email address as the recipient.

Respiratory Therapy Services Billing. As part of ongoing finance and accounting processes by the Hospital's Respiratory Therapy (RT) organizational unit, a report of all billable services provided by respiratory therapists is automatically generated daily. This report contains codes for Respiratory Therapy services provided to patients. Three specific codes associated with resuscitation are often used: *Cardiac Arrest, Intubation Assist, and Manual Ventilation*. This report is sent from the billing system as a comma separated values (CSV) file to the RT manager. The manager created an email inbox rule to forward this to the REACH email address.

Virtual Code Blue (VCB) Button. Prior to the development of the VCB button, when no notification source was activated, but a member of the MDQI group knew of a pediatric cardiac arrest, a manual entry would be made via the User Interface by a system administrator. The VCB notification allows for the same functionality through a secure web-based form and by any member of the organization. This form creates a notification and inserts it directly into the database, while simultaneously initiating the data collection process. This was developed as part of the System Logic and User Interface application.

Development: Organizational Enterprise Email

Microsoft Exchange Server (Microsoft. Redmond, WA) is this institution's enterprise email system. No custom development or server-level modifications were necessary. A dedicated email account was created which required a formal request to system administrators. A feature known as "inbox rules" allow for an end-user to define a number of automated tasks to be performed on messages as they arrive. This feature was leveraged to identify Organizational IT system generated notifications and forward these to the MDQI listserv. Determining valid emails consisted of one or more conditions based on sender email address and known keywords being satisfied.

Development: Database

The database solution used is Microsoft SQL Server Express Edition (64-bit) Version 10. It consists of 20 tables that provide data storage and relationship definitions. These provide storage and structure to standardize all IT systems notification data from free-text message formats to that which allows for the creation of relationships between notifications, events (including type and location), and collected smart defibrillator and bedside monitor data.

Development: System Logic and User Interface

The System Logic and User Interface were developed using ASP.NET 4.5 Web Forms (C#) and runs on Internet Information Services (IIS) version 7.5. This application requires a SSL connection, using a SHA-256, RSA (2048 bit) certificate. This application is accessible only while on the institutional network or connected remotely through a secure VPN connection, using a fully qualified domain name managed by the institutional DNS. Authentication is also managed using the institutional single sign-on (SSO) service, whereas authorization is managed by the system database. Web forms were developed to provide for management of notification, event, and smart defibrillator and bedside monitor data, as well as data export and analysis.

Development: Listserv

The listserv is provided as an institutional communication tool powered by Sympa (RENATER. Paris, France). This tool is configured such that only the REACH email service and list members can send to it, and that any reply is a reply-all.

Development: Notification Polling Service

The Notification Polling Service is a Windows Service Application, developed in C# and running on an institutional server. This application uses the Exchange Web Services Managed API v2.0 (Microsoft. Redmond, WA.) to interact with the REACH mailbox, and a data access library providing database access. This service checks for new messages every 10 seconds and manages previous interactions with the system through the pre-existing "read-unread" built-in feature of Exchange as well as a check of the message's GUID presence in the database. This allows for MS Exchange, the database, or the polling service to be offline for any number of reasons, but resume normal operation (particularly processing of notifications and creation of events) as soon as all are available.

Deployment

The system was developed over a 6-month period, tested for 2 months, and launched January 1, 2013; reporting and analysis features were added in 2014. Code Blue Button, EHR, and Emergency Response Paging notification sources were integrated at the launch. Manual entries of notifications began in February of 2013, RT Billing reports in September 2014, and VCB in November of 2014. The PET program began in November of 2015 and related PING notifications were integrated at that time. As notifications were generated and sent to the system, each was associated with an event; multiple notifications could be linked to the same event. An event location was associated with one of 10 possible care areas (Table 1.) and designated as a CA event or not. For events that were designated CA, if smart defibrillator and/or bedside monitor data were collected this was added to the event record.

Care Area	Description	Children's Center
CLINIC	Outpatient treatment areas	YES
FLOOR	Inpatient non-acute, non-critical care areas	YES
IMAGING-DIAGNOSTIC	CT, MRI, X-ray	YES
NICU	Neonatal ICU	YES
NON-CHILDRENS-HOSPITAL	On the medical campus, clinical or non-clinical area	NO
OTHER-CHILDRENS-HOSPITAL	Non-clinical area	YES
PACU	Peri-anesthesia care area	YES
PEDS-ED	Pediatric emergency department	YES
PEDS-OR	Pediatric Operating Rooms	YES
PICU	Pediatric ICU (cardiac and non-cardiac)	YES

Figure 3. Notification and Event Location Types.

RESULTS

Surveillance System Identification and Detection of Events

For the period 1/1/2013 through 12/31/2015, there were 2,986 unique notifications associated with 2,145 events, of which 317 were designated as cardiac arrest requiring chest compressions and or defibrillation. There were 1.4 notifications per event (Range: 1-7). Seventy percent (70%) of events had three or less notifications. Only three events had the maximum (seven) notifications observed; all were CA events. CA events made up approximately 15% of all events detected by the surveillance system.

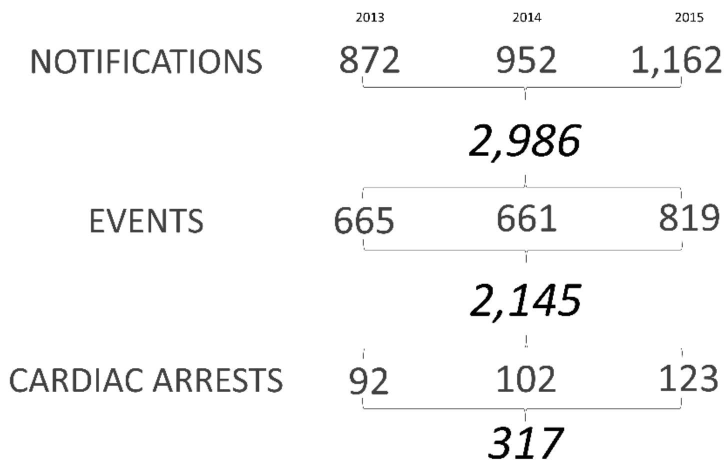

Figure 4. Aggregate and Yearly Frequency of pediatric notifications, events, and cardiac arrests

Notifications, Events, and Cardiac Arrest by Care Area

The PICU, FLOOR, and PEDS-ED were the top three Notification generators with 983, 1030, and 365 respectively. These care areas also had the most events (PICU:854, FLOOR:512, PEDS-ED:315) however the PICU and PEDS-ED accounted for 65% of all Cardiac Arrest events whereas FLOOR care areas were responsible for only 3% of all pediatric CA events.

CARE AREA	Notifications (n=2,986)	Events (n=2,145)	Cardiac Arrest (n=317)
CLINIC	42 (1%)	35 (2%)	0 (0%)
FLOOR	1,030 (34%)	512 (24%)	9 (3%)
IMAGING-DIAGNOSTIC	43 (1%)	19 (1%)	7 (2%)
NICU	225 (8%)	170 (8%)	52 (16%)
NON-CHILDRENS-HOSPITAL	51 (2%)	33 (2%)	5 (2%)
OTHER-CHILDRENS-HOSPITAL	50 (2%)	40 (2%)	8 (3%)
PACU	113 (4%)	85 (4%)	3 (1%)
PEDS-ED	365 (12%)	315 (15%)	64 (20%)
PEDS-OR	84 (3%)	82 (4%)	26 (8%)
PICU	983 (33%)	854 (40%)	143 (45%)

Table 1. Aggregate Event, Notifications and Cardiac Arrest Counts and Percentages by Care Area . % values are percent of column totals.

Approximately 20% of PICU and PEDS-ED notifications were CA-related as were events that were CA-related. The proportion of PEDS-OR events and notifications that were CA-related was 32%, and the NICU and IMAGING-DIAGNOSTIC care areas had 30 and 37% of events being CA-related respectively; 40% of notifications were CA-related for both areas.

CARE AREA	NOTIFICATIONS THAT ARE CARDIAC ARREST RELATED/NOTIFICATIONS (%)	EVENTS THAT ARE CARDIAC ARREST RELATED/EVENTS (%)
CLINIC	0/42 (0%)	0/35 (0%)
FLOOR	32/1030 (3%)	9/512 (2%)
IMAGING-DIAGNOSTIC	17/43 (40%)	7/19 (37%)
NICU	96/225 (43%)	52/170 (31%)
NON-CHILDRENS-HOSPITAL	11/51 (22%)	5/33 (15%)

OTHER-CHILDRENS-HOSPITAL	8/50 (16%)	8/40 (20%)
PACU	6/113 (5%)	3/85 (4%)
PEDS-ED	80/365 (22%)	64/315 (20%)
PEDS-OR	27/84 (32%)	26/82 (32%)
PICU	216/983 (22%)	143/854 (17%)
Total	493/2986 (17%)	317/2145 (15%)

Table 2. Proportion of Notifications and Events that are CA-related, by Care Area

Differences in Notifications per Event given Cardiac Arrest Event Status

When comparing the total number of notifications per event by cardiac arrest status, there was a statistically significant difference between the two groups (CA: 1.6 vs. Non-CA: 1.4; $p<0.001$; Wilcoxon Rank-sum). Of note, on detailed evaluation these differences varied by year and by location and warrant further exploration.

	2013	2014	2015	Total
Cardiac Arrest Event				
CLINIC	-	-	-	-
FLOOR	2.5	-	**4.4**	3.6
IMAGING-DIAGNOSTIC	2.3	-	2.5	2.4
NICU	**1.5**	1.8	**2.1**	1.8
NON-CHILDRENS-HOSPITAL	3.0	1.0	1.0	2.2
OTHER-CHILDRENS-HOSPITAL	1.0	1.0	1.0	1.0
PACU	-	2.0	-	2.0
PEDS-ED	1.2	1.3	1.3	1.3
PEDS-OR	1.0	1.0	1.1	1.0
PICU	**1.3**	**1.4**	**1.7**	1.5
Total	1.4	1.4	**1.8**	**1.6**
Non-Cardiac Arrest Event				
CLINIC	1.4	1.2	1.0	1.2

FLOOR	1.8	2.0	**2.1**	2.0
IMAGING-DIAGNOSTIC	1.0	2.1	2.5	2.2
NICU	**1.1**	1.2	**1.0**	1.1
NON-CHILDRENS-HOSPITAL	1.6	1.4	1.3	1.4
OTHER-CHILDRENS-HOSPITAL	1.2	1.8	1.1	1.3
PACU	1.3	1.5	1.1	1.3
PEDS-ED	1.1	1.1	1.2	1.1
PEDS-OR	1.1	1.0	1.0	1.0
PICU	**1.0**	**1.1**	**1.1**	1.1
Total	1.3	1.4	**1.4**	**1.4**

Table 3. Notifications per Event by Care Area and Year, stratified by Cardiac Arrest status. **Bold indicates statistically significant difference between the value for the care area and year and its complement in the comparison cardiac arrest status group.**

Surveillance Performance

Examining the type of notification sources associated with each CA event allowed for the determination of whether or not the event would have been detected had the surveillance system not been put in place had the previous system continued status quo. Events were flagged as having been identified by any other source other than the EHR or the Emergency Response Paging (methods available and utilized prior to the deployment of REACH). 100% of the PEDS-OR CA events would not have been detected and/or reported, over 70% of PICU, and approximately 50% of both PEDS-ED and NICU events would not have been detected and/or reported in our institutional database.

	2013	2014	2015	TOTAL
CARE AREA				
CLINIC	-	-	-	-
FLOOR	0/4 (0%)	-	0/5 (0%)	0/9 (0%)
IMAGING-DIAGNOSTIC	0/3 (0%)	-	0/4 (0%)	0/7 (0%)
NICU	10/13	8/15	8/24	26/52

	(77%)	(53%)	(33%)	(50%)
NON-CHILDRENS-HOSPITAL	1/3 (33%)	1/1 (100%)	1/1 (100%)	3/5 (60%)
OTHER-CHILDRENS-HOSPITAL	2/3 (67%)	2/2 (100%)	3/3 (100%)	**7/8 (88%)**
PACU	-	1/3 (33%)	-	1/3 (33%)
PEDS-ED	16/23 (70%)	9/18 (50%)	6/23 (26%)	31/64 (48%)
PEDS-OR	**5/5 (100%)**	**12/12 (100%)**	**9/9 (100%)**	**26/26 (100%)**
PICU	**34/38 (89%)**	**40/51 (78%)**	**28/54 (52%)**	**102/143 (71%)**
Total	68/92 (74%)	73/102 (72%)	55/123 (45%)	196/317 (62%)

Table 4. Proportion of CA events detected only via implementation of the REACH surveillance system.

Smart Defibrillator and Bedside Monitor Data Collection

Over the period there was an increase in the proportion of CA events that had defibrillator records, defibrillator records with quality of CPR data, and bedside monitor data collected. More records were collected than had usable quality of CPR data. Defibrillator pads capable of measuring quality in patients smaller than 25kg were not available until 2014, thus skewing these results. When evaluating events that had both usable CPR data from the defibrillator and bedside monitor data this proportion increased from year to year, but was still relatively low (2013:1%; 2014:18%; 2015:27%).

Figure 5. Proportion of CA Events with Smart Defibrillator and Bedside Monitor Data Collected, by Year

DISCUSSION

In 2015 the National Academies described a framework for "improving patient outcomes from cardiac arrest". This framework rests on a foundation of comprehensive surveillance and reporting underpinned by reliable and accurate data (Graham 2015). Several national-level registries exist in the United States, where data for both in-hospital and out-of-hospital cardiac arrest can be reported, aggregated and analyzed (Davis 2007 , McNally 2009, Merchant 2012). These have increased capacity in the resuscitation quality improvement and science fields by way of access to resources (the registries themselves) and the generation of reports for users and researchers. The design of these registries are informed by best practices and based on published standards such as the Utstein templates for resuscitation registries (Jacobs 2004, Cummins 1991, Zaritsky 1995, Cummins 1997). Although these design features help to ensure that the data submitted are standardized and can be rigorously analyzed, they do little to ensure that all eligible events from contributing institutions are detected and their data collected and submitted. This is especially reflected in the variability in reported incidence of IHCA and even more so with the wide range of pediatric estimates of CA (Chan 2010, Morrison 2013, deMos 2006). Active and comprehensive surveillance is necessary at the individual hospital level in order to both ensure not only reliability and accuracy of the data being submitted but also its completeness. Without complete event detection, the true incidence of pediatric cardiac arrest will be underestimated, survival rate estimates may be inaccurate as a result and perhaps even more troubling systematic selection biases may be lurking in the larger national registries.

For example, in 2011, at this institution there were only 11 detected in-hospital pediatric cardiac arrests that were evaluated as part of the hospital-level quality improvement initiative in place at the time. The main objective of this initiative was to enter events into the national resuscitation registry (American Heart Association's "Get With the Guidelines-Resuscitation").

In 2012, this number increased to fourteen. Eight occurred in the PICU, four on the general wards (non-ICU), one in a diagnostic area (MRI), and one in the emergency department. According to these records there were "0 pediatric events" in February, August, September, and November. When reviewed by members of the CPR advisory committee, and compared to other institutions, these numbers appeared to under-represent the actual frequency of events.

Using the PICU as an example, in 2011 and 2012 there were ~ 2000 admissions each year (1,990 and 2,000 respectively). Current reported rates of cardiac arrest in PICUs are estimated to range from 1.8% to 5.5% of admissions (Suominen 2000, Ronco 1995, de Mos 2006). Using these rates the expected number of cardiac arrests that should be observed in the PICU is between 36 and 110. For 2012 the observed number of events was 8 versus the expected of at least 36; further aiding in validating the concern that pediatric CA events were being missed using the methods of detection in place at the time, ultimately contributing to an under-estimation of events and potentially a mis-characterization of the nature of the disease.

After the implementation of the REACH surveillance system what was observed and what was expected began to align. First, determining the number of PICU events detected only after the REACH system deployment allowed to determine and count those events that would have been identified had the system not been put deployed. The count of events identified only by previous methods were similar with historical counts (Table 4) suggesting the system was not missing any that were previously being detected. Second, the difference between CA events that would have been detected and what was detected show a true increase in events captured (eg. 2013: 4 versus 38 events). Lastly, the calculated incidence based on the detected frequency of these events falls within the expected estimates as reported in the literature (Suominen 2000, Ronco 1995, Chan 2010, Morrison 2013, Nadkarni 2006). The measured incidence for PICU events (CA / admissions) was approximately 2% for each year (2013: 38/2100 (1.8/100 admissions); 2014: 51/2262 (2.2/100 admissions); 2015:54/2203 (2.5/100 admissions)), suggesting that the system was approaching 100% capture in the PICU.

The increase in detected events for the entire pediatric population by year and in previously under-reported care areas indicates that the system objective to identify every pediatric cardiac arrest is on its way to being met. By leveraging additional electronic sources to identify candidate events and a multi-disciplinary team to verify cardiac arrest status a more effective system than previously in place has been demonstrated over three years. As comprehensive local surveillance processes or systems such as the REACH system are deployed, an increasingly representative set of accurate and reliable pediatric CA event data, less vulnerable to selection bias, can be submitted to national registries.

Detection of every event not only promotes the completeness, accuracy, and reliability of registry data, it also provides for more opportunities to critically and objectively debrief these events. Technological advances in recent years have allowed for, 1) patient and resuscitation performance data capture during cardiopulmonary arrest, 2) real-time feedback, and 3) post-event evaluation of healthcare provider performance. A systematic review of these technologies suggests that their use during training helps to improve skill retention (Yeung 2009). Despite the ability for these devices to provide feedback during resuscitation, it is unclear whether or not this alone is sufficient to affect sustained healthcare provider performance (Edelson 2008, Abella 2005, Bohn 2011). Data collected during resuscitations has been shown to help improve subsequent CPR quality performance when used during cold debriefings (Edelson 2008, Jiang 2010, Wolfe 2012). Couper and Perkins assert that objective performance data is a key requirement for cold debriefing (where individuals or teams are provided with feedback sometime after the event). (Couper 2013). This is particularly important for determining guideline compliance, identifying poor performance, understanding high performance, and using all as opportunities to reinforce a shared mental model of what is exquisite CPR. These debriefings can provide opportunities to confirm the accuracy of data that will be entered in to the GWTG-R registry, as medical records are often incomplete or inaccurate (Couper 2012). In 2014 and 2015 although not every event's bedside monitor data was captured, [2014: 51/102 (50%); 2015: 65/123 (53%)] the ability to confirm, or identify, the true: initial rhythm, time of pulselessness, time to starting compressions, time from shockable rhythm to defibrillation was possible, as well as use of a device to confirm endotracheal tube placement. Bedside data are either lost due to the patient being discharged from the monitor system, time passing and data being overwritten, or system limitations (e.g. the OR monitor system does not interface with the data collection tool used in other care areas). Highlighting the importance of this data during debriefing has motivated leadership within each care area to implement processes to ensure the data are not discharged or deleted prior to their collection. With the addition of a project coordinator, and two volunteer clinical staff, to provide capacity to collect monitor data outside daytime hours and on the weekends, the proportion of all events with bedside data captured in 2016 has increased to 72%.

CONCLUSION

Although this system has increased the detection of events across the pediatric care areas, particularly in acute and critical care settings, it is still challenging to know if every event is being detected. More work is needed to collect appropriate denominator data for all care areas in order to effectively analyze CA incidence for comparison against similar institutions, as well as, data mining of the EHR to determine the missed event rate, or to generate live-time alerting of CA events to be used in conjunction with or supplemental to a surveillance system such as this.

The implementation of a surveillance system to identify pediatric cardiac arrest events, using organizationally available notification sources has resulted in an increase in CA event detection. Prior to the development of the REACH system at most 14 events per year were detected. After deployment this has increased almost 9-fold to 123 pediatric CA per year. Had the system not been implemented, and using pre-deployment methods of detection, 100% of PEDS-OR events would have been missed along with 50-70% of events the PICU, NICU and ED. As pediatric CA events are detected, the REACH system triggers patient and performance data collection mechanisms used to drive weekly debriefing of events. Over the period both smart defibrillator and bedside monitor data collection increased and were used during debriefings. For 2014 and 2015 however, 16-20% of defibrillator records collected did not contain quality of CPR data. Methods to collect bedside monitor were not available until the end of 2013. Both methods and processes were formalized in early 2014 resulting in approximately 50% of events having monitor data collected.

These data not only provide objective assessment of guideline compliance and level of CPR quality and potential subsequent performance improvements, but they also allowed for confirmation of key data elements submitted to GWTG-R thus improving accuracy and reliability of the overall registry. An effective surveillance system, objective performance data and active quality improvement initiatives can drive efforts to further improvements in the quality of resuscitation provided to children everywhere.

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CHAPTER 4

1,625 MINUTES OF PEDIATRIC CARDIOPULMONARY RESUSCITATION: ANALYSIS OF QUALITY PERFORMANCE AND ACUTE SURVIVAL IN A LARGE ACADEMIC MEDICAL CENTER, 2013-2015

INTRODUCTION

Despite increases in published survival rates for children suffering from cardiac arrest these rates still remain low. Less than 50% of children experiencing an in-hospital cardiac arrest (IHCA) will survive to discharge. The chance to survive to discharge is driven completely by whether or not the pediatric victim of cardiac arrest acutely survives the initial event. Acute survival is defined by having a return of spontaneous circulation (ROSC) lasting more than twenty minutes. Patients may also experience post-resuscitation survival and return of circulation via successful placement on extra-corporeal membrane oxygenation (ECMO) support. Unfortunately, a relatively large proportion of pediatric patients do not experience acute survival, with reports of successful resuscitation reaching only as high as 75%- factors driving acute survival remain elusive (Merchant 2011, López-Herce 2013, Meert 2009, Nadkarni 2006).

Since the discovery of CPR in 1960 at Johns Hopkins, recommendations for how to perform this life-saving technique have been made by multiple individuals, professional organizations, and groups of experts (Kouwenhoven 1960, AHA 2005, AHA 2010, Meaney 2013). These guidelines have been informed by experiments using human subjects and animal models, clinical experience and expertise, and recently chest compression derived-data obtained from devices designed to provide real-time and post-event data on performance. Animal data suggest linkages between performance and acute survival, however these models often do not reflect the complex pathways of pediatric cardiac arrest, instead focusing on standardization of the mechanism of injury. Furthermore, these studies, though providing valuable data on hemodynamics and physiology, often analyze aggregate performance data, rely heavily on standardization of the study protocol to justify less sophisticated statistical comparisons and assume an otherwise healthy model with no preexisting conditions (Shafner 1994, Hamrick 2014, Morgan 2017).

Although chest compression performance and survival has been explored in adult patients, no significant associations between the two have been observed (Abella 2005). Analysis of acute survival as a function of guideline compliance metrics using accurate and reliable performance data from pediatric resuscitation has never been reported.

METHODS

On January 1, 2013, the Johns Hopkins Children's Center initiated a quality improvement (QI) program to 1) identify every cardiac arrest event, 2) review (a) patient history and events leading up to the event, (b) objective quality data, (c) teamwork and communication, 3) use the active review to gain insight to interactions that contributed to high or low performance and 4) implement interventions based on this insight to improve subsequent performance. Identification of these events was made possible through the implementation of a pediatric cardiac arrest surveillance system (as described in Chapter 3 "**Design, Development and Deployment of a Pediatric Cardiac Arrest Surveillance System**"). Objective CPR performance was assessed for adherence to the 2010 American Heart Association (AHA) CPR quality guidelines for depth, rate and chest compression fraction (CCF) and discussed during debriefing. Event data were abstracted and entered into the surveillance database as part of the QI initiative; the IRB approved use of these data for this retrospective study. Resuscitation events were included in this study if the patient was $\leq$ 21 years of age while being treated by a pediatric service in the Children's Center and if a complete defibrillator data file was successfully retrieved after the event.

Data Analysis: Variables and Definitions

Patient

The following patient-level elements were extracted from the QI database for use in analysis: age at date of event, gender, weight, number of previous cardiac arrests, and 20 pre-existing conditions at time of event as defined by the AHA GWTG-R registry (see: https://osstatic.outcome.com/online_doc_qi/GWTGR/coding_instruction/ResuscitationCodingInstructions_print.pdf).

Event

The following event-level elements were extracted for use in analysis: date and time of event, duration, location, initial rhythm, and acute survival status. Date and time were used to create binary variables to define whether or not: 1) the event happened during the day versus evening using spans described by Girotra et al (Day: 7A-11p vs. Night:11p-7A), and 2) the event happened during the week or on a weekend day. Location data were used to create categorical variables to describe the in-hospital service providing care during the resuscitation (PICU, ANESTHESIA, EMERGENCY MEDICINE, FLOOR) as well as whether or not CPR was initiated inside the hospital or out-of-hospital (IHCA v. OHCA). Cases in which CPR was initiated out-of-hospital and then transferred to an in-hospital team were included for guideline compliance analyses but not for survival analyses. Acute survival was defined as sustained ROSC for greater than 20 minutes; events in which the patient was successfully placed on ECMO were not included.

Measuring Parameters of CPR Quality

Prior to the launch of this QI effort all defibrillators in the Children's Center were standardized to one model, and deployed with identical settings configured by this institution's biomedical engineering department. The model selected was the ZOLL R Series defibrillator

(ZOLL Corp. Chelmsford, MA) with One-step® CPR electrodes. This system allowed for the collection of chest compression accelerometer-based data. Although the manufacturer-provided data-review software allowed for some evaluation of performance data, custom software was needed to standardize and automate the transformation of raw ZOLL data into variables required for analysis. The results of the custom software were accelerometer-derived data which described in detail the quality of CPR related to chest compressions and interruptions. These variables were used during statistical analyses of performance and a logistic regression analysis of acute survival.

Epochs

We defined an epoch as a 60-second period during which resuscitation is ongoing. An event can have one or more associate epochs. Time-zero for event epochs begins with the detection of the first chest compression after the ZOLL R Series One Step electrode was placed on the patient.

Quality Metrics

We selected thresholds to define chest compression depth and rate compliance based on the AHA 2010 guidelines for pediatric patients. We also incorporated consensus statement, best-practice recommendations, and previous definitions for interruption-related metrics.

Metric	Quality Compliant Definitions
Depth	
$\leq$ 1 year old	$\geq$ 1.5inches
> 1 year old	$\geq$ 2.0 inches
Rate	100-120 compressions per minute
Chest Compression Fraction	$\geq$ 80%
Interruption	$\geq$ 3 seconds
Long Interruption	$\geq$ 10 seconds

Figure 1. Thresholds used to define quality compliant chest compression and interruption-related metrics.

Epoch-level Variables

Quality at the epoch-level was defined by the following: interruptions, depth, rate, chest compression fraction, as well as depth *and* rate *and* chest compression fraction ("depth+rate+chest compression fraction"). Frequency of interruptions longer than 3 seconds was determined as was the frequency of interruptions of 10 or more seconds. Average chest compression depth for the epoch determined compliance for depth. Average chest compressions per minute for the epoch determined compliance for rate. Chest compression fraction was defined as the time in seconds with chest compressions during the epoch divided by 60. Interruptions lasting longer than 3 seconds contributed to non-chest compressions time and was subtracted from the numerator; chest compression fractions greater than or equal to 80% were deemed compliant.

Event-level Variables

Epoch-level variables were used to create four additional variables at the event-level. Percent of event epochs where the value was compliant for: depth, rate, chest compression fraction, and all three was determined by dividing the frequency of compliant epochs by the event total epoch count. The accelerometer-based data allowed for evaluation of each individual chest compression in terms of depth and rate. Compliance thresholds above these two variables were created that describe the percent of event chest compressions compliant for depth and for rate. Frequency of interruptions for an event was determined in the same way described for those at the epoch-level. We also included the more common variables of event averages for depth and rate as well as overall event chest compression fraction and whether or not each overall measurement is compliant.

Data Analysis: Statistical Analyses

Statistical analyses were performed using Stata/IC 13.1 for Windows (StataCorp, College Station, TX). P-values of less than 0.05 were considered statistically significant for analyses. The primary outcome measure was acute survival defined as ROSC lasting more than 20 minutes. Secondary outcomes of interest included chest compression and interruption-related performance compliance analyzed over the study period as well as between the survivor and non-survivor groups.

Demographic

Patient level data were reported in aggregate as well as stratified by year. Total patients and number of previous cardiac arrests ever experienced by patients were reported. Median values and interquartile ranges were reported for continuous variables. Comparisons by year were made using the Kruskal-Wallis nonparametric test. Proportions were analyzed using Fisher's exact test or chi-square statistic. If overall differences were detected, 2x2 comparisons using Fisher's exact test were conducted to determine differences between years. Median and IQR age (in years) data were reported along with minimum and maximum age and patients were stratified into $\geq$ 1 year versus < 1 year-old categories and proportions reported; this was done to reflect a systematic difference in assessment of chest compression depth compliance based on age. Median and IQR values for weight in kilograms were calculated along with minimum and maximum values. Anatomic gender at birth was measured dichotomously as female or male and frequency and proportions determined. All pre-existing conditions variables were dichotomous and frequency and proportion were reported.

Events

Event level data was also reported in aggregate as well as stratified by year. The number of events and number of 60-seconds epochs were reported. Event duration data were non-normally distributed and reported as median values with IQR and analyzed using the Kruskal-Wallis nonparametric test. Gender, Day versus Night, Weekday versus Weekend, Out-of-hospital (OHCA) versus in-hospital cardiac arrest (IHCA), Care Designation and Initial Rhythm were all reported as frequencies and proportions with comparisons across years made using Fisher's exact or chi-square test statistic.

Quality

Performance was assessed using quality metrics (listed in Table 3) for comparison across years, using all event data, including both IHCA and OHCA data. Continuous data were non-normally distributed and assessed using the Kruskal-Wallis nonparametric test and frequencies were compared using Fisher's exact or chi-square test statistic.

Survival: Unadjusted
by event and patient characteristics

Event demographic comparisons were made by stratifying by acute survival outcome (i.e. ROSC sustained for > 20 minutes or not) using only IHCA event data. Survival was compared across year, duration of event in binned groups (1,2,3,4,5-10,10-15,15-20,20-25, 25+ minutes), measured duration, overall age, age $\geq$ 1 year and < 1 year-old, day versus night, weekday versus weekend, initial cardiac arrest rhythm, and care designation.

by quality characteristics

Quality comparisons of derived metrics (listed in Table 3) were performed by stratifying by acute survival (using only IHCA data). The decision to limit these survival comparisons to IHCA events was made because of the high potential for significant unknown pre-hospital performance. This potential performance bias could influence the survival experience of these out-of-hospital patients receiving care as part of a continuum in the hospital emergency department and potentially on to the intensive care unit, and as such was excluded from analysis.

by pre-existing conditions

Proportion and frequency of patients' pre-existing conditions were stratified by acute survival outcome.

Frequencies and proportions were compared using the chi-square test statistic or Fisher's exact statistic when cell frequencies were less than 10. All continuous data were non-normally distributed and comparisons made using the Wilcoxon rank-sum test, and multiple category comparisons made using the Kruskal-Wallis nonparametric test.

Survival: Adjusted
Multivariable logistic regression model building

In order to select patient, event, and quality characteristics associated with acute survival for inclusion in a multivariable logistic regression model the following model building process was undertaken. We first used results of the comparative associations of acute survival with event characteristics, quality measures, and pre-existing conditions to identify variables that were statistically significantly associated acute survival. We created a dichotomous variable to indicate events with an initial cardiac rhythm of bradycardia versus not. Backward-selection stepwise estimation was then performed to eliminate covariates with significance levels ≥ 0.20. Lastly quality related terms not retained by the stepwise elimination process were considered for inclusion in the model to provide point estimation and confidence intervals for variables of particular interest.

Results from analyses are presented as odds ratios (OR) and 95% confidence intervals (CI).

RESULTS

Population

During the study period, 81 pediatric patients experienced one or more cardiac arrests after which a ZOLL record was retrieved. Seventy-five percent of patients had only one cardiac arrest; the remaining had experienced a total of 2 (18%) and 3 (7%) CA events. The number of patients increased with year with significant changes in age between 2013 and 2014 and between 2013 to 2015. In 2013 the median age was 8.3 years old and the proportion of patients less than 1 year of age was 9%. The median age decreased to 2.1 and 1.6 in years 2014 and 2015 respectively. The proportions shifted to 36% and 38% , for less than 1 year-olds in years 2014 and 2015 respectively. Similar changes for weight were also observed with a decrease in the median weight in 2013 of 30 kg to 11 kg in 2015 (p for trend = 0.006). During 2014, pediatric pads became available for use in patients under the age of 8 years-old and less than 25 kg. Overall there were more males (58%) than females (42%) with no statistically significant changes in proportion over the time period, however the proportion of males increased from 55 to 60%. There were no significant changes across years for any of the 20 pre-existing conditions evaluated. Overall 10% of patients experiencing cardiac arrest had 0 known pre-existing conditions, and the top three most common pre-existing medical conditions were: respiratory insufficiency (64%), hypotension and/or hypoperfusion (30%), and metabolic/electrolyte abnormality (21%). Aggregate and annual patient demographic characteristics are presented in Table 1.

	2013	2014	2015	Total	p
# Patients	11	28	42	81	
# Having 0 Previous CAs	10	21	30	61	
# Having 1 Previous CAs	1	2	11	14	
# Having 2 previous CAs	0	5	1	6	
Age (years)					
median (IQR)	8.3 (3.7 -15.2)	2.1 (0.4-9.0)	1.6 (0.5-7.6)	2.9 (0.62-9.25)	**2013-14 p = 0.044, 2013-15 p=0.0124**; 2014-15 p=0.952
min-max	0.07-20.05	0.03-17.5	0.04-17.6	0.03-20.05	
< 1 year old n(%)	1 9%	10 36%	16 38%	27 33%	0.2
≥ 1year old n(%)	10 91%	18 64%	26 62%	54 67%	
Weight (kg)					
median (IQR)	30.0 (13.2-40.0)	13.0 (7.3-34.8)	11 (6.6-20.0)	12.9 (7.0-30.0)	2013-14 p = 0.0948, **2013-15 p=0.006**; 2014-15 p=0.4076
min-max	3.0-70.0	3.0-93.1	3.2-106.0	3.0-106.0	
Gender					
Female n (%)	5 45%	12 43%	17 40%	34 42%	1.00
Male n (%)	6 55%	16 57%	25 60%	47 58%	

Table 1. Aggregate and year-to-year patient demographics.

Events

1,625 sixty-second epochs of data were retrieved from 93 events over the period. The median event duration was 13 minutes with no significant changes by year. The gender distribution for events matched the distribution for the population with just under 60% of patients being male. More events took place during the 7a-11p time period (DAY:73% v. NIGHT:25%) though given the distribution of hours (7a-11p: 66%; 11p-7a 33%) the difference is not statistically significant (p=0.196). Similarly, more events occurred during the week than on the weekend (WEEK:81% v WEEKEND: 19%; p=0.123). The majority of events began as IHCA compared to OHCA, 71% v 29% respectively with no significant changes in distribution occurring over the period. More than 90% of events were designated as PICU (54%) or PED (41%) events with anesthesia and floor events contributing only 2 and 3% of quality data respectively. The most common initial cardiac rhythm was PEA (57%) followed by bradycardia (20%) and then asystole (14%); there were no significant changes in initial rhythm over the time period. Aggregate and year-to-year event characteristics are presented in Table 2.

	2013	2014	2015	Total	p
Events - n	11	34	48	93	
Epochs - n	152	674	799	1625	
Duration- median (IQR)	13 (3-22)	15 (4-25)	10.5 (5-21)	13 (4-22)	0.843
Female - n(%)	5 (46%)	16 (47%)	19 (40%)	40 (43%)	0.785
Male	6 (54%)	18 (53%)	29 (60.0%)	53 (57%)	
Day (7a-11p)	11 (100%)	24 (71%)	33 (69%)	68 (73%)	0.099
Night	-	10 (29%)	15 (31%)	25 (27%)	
Weekday	11 (100%)	28 (82%)	36 (75%)	75 (81%)	0.159
Weekend	-	6 (18%)	12 (25%)	18 (19%)	
OHCA	1 (9%)	10 (29%)	16 (33%)	27 (29%)	0.279
IHCA	10 (91%)	24 (71%)	32 (67%)	66 (71%)	
PICU	6 (55%)	20 (59%)	24 (50%)	50 (54%)	0.592
PED	4 (36%)	14 (41%)	20 (42%)	38 (41%)	
ANES	-	-	2(4%)	2 (2%)	
FLOOR	1 (9%)	-	2 (4%)	3 (3%)	
ASYSTOLE	1(9%)	6(18%)	6(13%)	13(14%)	0.929
BRADYCARDIA	2(18%)	7(21%)	10(21%)	19(20%)	
PEA	7(64%)	17(50%)	29(60%)	53(57%)	
PVT	1(9%)	3(9%)	1(2%)	5(5%)	
UNKNOWN	0(0%)	1(3%)	1(2%)	2(2%)	
VF	0(0%)	0(0%)	1(2%)	1(1%)	
	11(100%)	34(100%)	48(100%)	93(100%)	

Table 2. Aggregate and year-to-year event characteristics.

Chest compression and interruption quality

Improvements in the percent of all epochs compliant for depth, rate, chest compression fraction and depth+rate+chest compression fraction were measured over the 3-year period. With the exception of percent of epochs compliant for depth, (2013:56% - 2015:60%; p=0.07) all other measures saw statistically significant improvement over the time period. Percent of epochs compliant for rate increased from 33% to 78% (p=0.000), chest compression fraction from 72% to 84% (p=0.005) and the combination of all three from 22% to 43% (p=0.000). At the event level there were no significant changes in the median measurements of number, duration, or number of interruptions > 10 seconds over the period. The median and IQR of number of interruptions were low 1 (0-3); however, the maximum number of interruptions >10s were unexpectedly quite high (2013 n_{max}=7, 2014 n_{max} =29; 2015 n_{max} =13).Median values for percentages of each event's epochs compliant for each measure held steady or showed no significant change over the period with the exception of average rate which shows a statistically significant increase in median percentages compliant over the period (2013: 0.53 (0.0-0.79) – 2015: 0.87 (0.62-1.0; p=0.04). Similar results were observed when evaluating individual chest compressions; there was no significant difference in the percentage of chest compressions compliant for depth over the years (2013: 76% (0-97%); 2014: 80% (85-100%); 2015:68% (0-100%); p=0.65) however the increase in percent of chest compressions (compliant for rate) saw a 6-fold increase from 14% to 82% (p=0.015). Aside from 2013 with a small number of events with < 1 year-old patients, the percentage of all events when average depth was compliant was held in the 61-75% range, percentage of all events when chest compression fraction was compliant was held in the 73-85% range, and percentage of all events when average rate was compliant saw a significant increase from 45% to 79% (p=0.052). Yearly comparisons of all quality metrics along with actual depth, rate, and chest compression fraction median values are presented in Table 3.

	2013	2014	2015	Total	p
Quality Measures					
ALL EPOCHS (n)	152	674	799	1625	
DEPTH COMPLIANT; n (%)	85 (56%)	435 (65%)	479 (60%)	999 (62%)	0.07
RATE COMPLIANT; n (%)	50 (33%)	461 (68%)	619 (78%)	1130 (70%)	**0.000**
CCF COMPLIANT; n (%)	110 (72%)	542 (80%)	667 (84%)	1319 (81%)	**0.005**
DEPTH +RATE+CCF COMPLIANT; n (%)	33 (22%)	295 (44%)	347 (43%)	675 (42%)	**0.000**
EVENT (n)	11	34	48	93	
Interruptions (n); Median IQR	6 (3-26)	6 (1-28)	7 (3-19)	7 (2-20)	0.945
INTERRUPTIONS Duration (s); Median IQR	44 (20-154)	36 (7-135)	47 (19-142)	45 (14-142)	0.802
# INTERRUPTIONS > 10s; Median IQR	1 (0-3)	0 (0-3)	1 (0-2)	1 (0-3)	0.703
#INTERRUPTIONS > 10S; Maximum	7	29	13	29	
% EVENT EPOCHS Average DEPTH $\geq$ TARGET	0.85 (0.0-1.0)	0.79 (0.0-1.0)	0.74 (0.22-0.96)	.78 (0.12-0.96)	0.995
% EVENT EPOCHS Average RATE $\geq$ 100 < 120	0.53 (0.0-0.79)	0.73 (0.0-0.90)	0.87 (0.62-1.0)	.78 (0.4-0.96)	Overall - 0.06; 2013-14: 0.39; **2013-15: 0.04**;2014-15: 0.78
% EVENT EPOCHS CCF $\geq$ 80%	0.87 (0.57-1.0)	0.93 (0.67-1.0)	0.86 (0.71 -0.98)	0.89 (0.67-1.0)	0.32
% EVENT EPOCHS DEPTH & RATE & CCF TARGET COMPLIANT	0.28 (0.0-0.43)	0.32 (0.0-0.63)	0.44 (0.0-0.65)	0.33 (0.0-0.63)	0.30
% EVENT CHEST COMPRESSIONS DEPTH $\geq$ TARGET	0.76 (0.0-0.97)	0.80 (0.85-1.0)	0.68 (0.0-1.0)	0.69 (0.0-1.0)	0.65
% EVENT CHEST COMPRESSIONS RATE > 100 < 120	0.14 (0.0-0.8)	0.37 (0.04-0.97)	0.82 (0.45-0.96)	0.64 (0.1-0.9)	**0.015**
EVENT AVERAGE DEPTH; AGE $\leq$1 YEAR OLD	0.86 (0.86-0.86)	1.7 (0.96-1.8)	1.6 (1.5-1.8)	1.6 (1.3-1.8)	0.423
EVENT AVERAGE DEPTH; AGE >1 YEAR OLD	2.3 (1.6-2.6)	2.1 (1.8-2.4)	2.0 (1.6-2.3)	2.1 (1.7-2.4)	0.319
EVENT AVERAGE RATE	114 (106-125)	116 (112-124)	109 (106-116)	114 (108-119)	**0.002** 2013-14: 0.459 2013-2015:0.206 **2014-2015:0.0005**
EVENT CCF	0.91 (0.76-0.97)	0.94 (0.87-0.98)	0.93 (0.86-0.96)	0.93 0.84-0.97)	0.246

COMPLIANT EVENT AVERAGE DEPTH AGE ≤1 YEAR OLD (n=27)	0/1 (0%)	7/11 (63%)	12/16 (75%)	19/28 (68%)	0.283
COMPLIANT EVENT AVERAGE DEPTH AGE >1 YEAR OLD (n=	7/10 (70%)	14/23 (61%)	17/32 (53%)	38/65 (59%)	0.584
COMPLIANT EVENT AVERAGE RATE	5 (45%)	21 (62%)	38 (79%)	64 (68%)	***0.052***
COMPLIANT EVENT CCF	8 (73%)	28 (82%)	41 (85%)	77 (83%)	0.536

Table 3. Year-to-year comparisons of all quality metrics.

Unadjusted Survival

When evaluating differences in acute survival at the event level there were no significant differences over years; overall 70% of patients that had usable ZOLL data had ROSC for 20 or more minutes, with no significant year-to-year changes. Percent experiencing acute survival inverted at the event duration lasting more than 20-minute mark, with the vast majority of patients who survived experiencing shorter cardiac arrest durations- median duration of events for survivors and non-survivors was 5 and 29 minutes respectively and was statistically significantly different (p=0.0001). Age, time of day, weekend versus weekday, and care designation were not significantly different between survivor groups and across categorical groups. Initial cardiac rhythm appeared different, between groups when comparing those surviving bradycardic events (89%) against all others (67%) (p=0.29). Comparisons of acute survival by patient and event level characteristics are presented in Table 4.

	ACUTE SURVIVAL +	n=66	ACUTE SURVIVAL -
Events			
2013	8 (17%)		2 (10%)
2014	18 (40%)		6 (30%)
2015	20 (44%)		12 (60%)
		0.448	
2013-15	46		20
Duration (minutes)			
1	3 (7%)		0 (0%)
2	11 (24%)		1 (8%)
3	4 (9%)		0 (0%)
4	3 (7%)		0 (0%)
≥5<10	11 (24%)		2 (10%)
≥10<15	6 (13%)		0 (0%)
≥15<20	5 (11%)		2 (10%)
≥20<25	2 (4%)		4 (20%)
25+	1 (2%)		11 (56%)
		0.000	
Duration (minutes) median (IQR)	5 (2-11)		29 (19.5-50.0)
		0.0001	
Age (years) median (IQR)	3.5 (0.96-10.5)		4.9 (2.0-9.9)
		0.494	
Weight (kg)	14.1 (7.4-36)		16.6 (11.1-29)
median(IQR)		0.955	
Age < 1 year	12 (26%)		3(15%)
Age ≥ 1 year	34 (74%)		17 (85%)
		0.323	
Time			
Day (7a-11p)	34 (74%)		13 (65%)
Night	12 (26%)		7 (35%)
		0.462	
Day			
Weekday	38 (83%)		15 (75%)
Weekend	8 (17%)		5 (25%)

		0.475	
Initial Rhythm			
ASYSTOLE	1 (2%)		0 (0%)
BRADYCARDIA	16 (35%)		2 (10%)
PEA	25 (54%)		16 (80%)
PVT	2 (4%)		2 (10%)
UKNOWN	1 (2%)		0 (0%)
VF	1 (2%)		0 (0%)
		0.248	
Location			
ANES	2 (4%)		0 (0%)
PED	10 (22%)		4 (20%)
FLOOR	3 (7%)		0 (0%)
PICU	31 (67%)		16 (80%)
		0.474	

Table 4. Comparisons of acute survival by patient and event level characteristics.

Of all the unadjusted analyses of chest compression quality and interruption-related measures by acute survival, only interruption-related measures revealed statistically significant differences between the two groups: number of interruptions, interruption duration, and number of interruptions greater than 10 seconds were significantly different between the two groups. Comparing those who did not survive to those that did, the median number of interruptions was almost five-times higher, the median duration of interruptions was 5 times as long, the absolute difference in median number of interruptions greater than 10 seconds was 3.5, and the median maximum number of interruptions greater than 10 seconds was 29 (compared to 5 seconds in the Acute Survival+ group). Despite these differences in interruption-related metrics, median chest compression fractions for both groups were well above the 80% threshold set for compliance (Acute Survival +: 0.94 (0.85-0.99); Acute Survival - 0.94 (0.90-0.96); p= 0.695) and 86% of all epochs for both groups were chest compression fraction compliant. Depth and rate performance was equivalent between the groups, though all depth and rate measures evaluated only achieved compliance ranging from

40 to 80%. Comparisons of all quality metrics along with actual depth, rate, and chest compression fraction median values between those who achieved ROSC and those who did not are presented in Table 5.

The final multivariable logistic model included: Weight (kg), was PICU event (Y|N), number of previous arrest events, initial rhythm was bradycardia (Y|N), number of interruptions greater than 10 seconds, percent of event epochs when epoch average depth was compliant, and percent of event epochs when epoch average rate was compliant. Table 6 shows the association between quality measures and acute survival after adjusting for patient and quality performance factors. Having a bradycardic arrest increased the odds of acute survival (OR 11.9; 95% C.I. 1.3, 116.0; p=0.033). Per unit increase in interruptions greater than 10 seconds in duration was associated with a decrease in the odds of acute survival (OR 0.53; 95% C.I. 0.36, 0.80 p=0.002). The percentage of event epochs compliant for depth or rate was not associated with acute survival, neither was patient weight, number of previous cardiac arrest events, or whether or not the patient was in the intensive care unit.

	ACUTE SURVIVAL +	ACUTE SURVIVAL -	p
Quality Measures	n=1053		
All Epochs (n)	380	673	
Depth Compliant; n (%)	250 (66%)	414 (62%)	0.168
Rate Compliant; n (%)	270 (71%)	484 (72%)	0.765
CCF Compliant; n (%)	328 (86%)	578 (86%)	0.846
Depth +Rate+CCF Compliant; n (%)	172 (45%)	297 (44%)	0.723
Event	46	20	
Interruptions (n); Median IQR	3 (1-7)	14.5 (5.5-26.5)	**0.0005**
Interruptions Duration (s); Median IQR	20.6 (4.4 -43.7)	103.2 (48-300.1)	**0.0001**
# Interruptions > 10s; Median IQR	0 (0-1)	3.5 (1.0-6.5)	**0.0001**
#Interruptions > 10s; Maximum	5	29	
% Event Epochs Average Depth ≥ Target	0.82 (0.0-1.0)	0.73 (0.31-0.92)	0.881
% Event Epochs Average Rate ≥ 100 < 120	0.68 (0.0-1.0)	0.84 (0.61-0.98)	0.192
% Event Epochs CCF ≥ 80%	0.97 (0.67-1.0)	0.90 (0.85-0.94)	0.503
% Event Epochs Depth & Rate & CCF Target Compliant	0.33 (0.0-0.6)	0.36 (0.22-0.76)	0.156
% Event Chest Compressions Depth ≥ Target	0.46 (0-0.99)	0.21 (0-0.97)	0.732
% Event Chest Compressions Rate > 100 < 120	0.62 (0.14-0.92)	0.83 (0.35-0.96)	0.424
Event Average Depth; Age ≤1 Year Old	1.6 (1.1-1.9)	1.7 (1.5-2.1)	0.471
Event Average Depth; Age >1 Year Old	2.14 (1.6-2.5)	2.14 (1.8-2.3)	0.968
Event Average Rate	112 (107-122)	114 (109-117)	0.616
Event CCF	0.94 (0.85-0.99)	0.94 (0.90-0.96)	0.685
Compliant Event Average Depth Age ≤1 Year Old	8(67%)	2(67%)	0.736
Compliant Event Average Depth Age >1 Year Old	20(59%)	10(59%)	0.616
Compliant Event Average Rate	27(59%)	16(80%)	0.08
Compliant Event CCF	39(85%)	19(95%)	0.232

Table 5. Comparisons of acute survival by quality performance metrics.

Characteristic	Unadjusted Odds Ratio	95% CI	Adjusted Odds Ratio	95% CI	P>z
Weight (kg)	1.00	0.97-1.03	1.01	0.97 - 1.05	0.62
Is PICU Patient	0.52	0.14-1.81	0.53	0.08 - 3.71	0.52
# of Previous Arrest Events	0.48	0.22-1.06	0.56	0.17 - 1.90	0.35
Is Bradycardic Arrest	4.8	0.99-23.35	12.57	**1.11 - 142.69**	**0.04**
Number of Interruptions > 10 seconds	0.54	0.37-.078	0.53	**0.36 - 0.80**	**0.002**
Event Average Depth Compliant	1.04	0.35-3.03	1.07	0.17 - 6.74	0.94
Event Average Rate Compliant	0.36	0.10-1.23	0.18	0.03 - 1.13	0.07

Table 6. Multivariable logistic regression of the association between odds of acute survival and patient, event, and quality performance characteristics.

DISCUSSION

This study has provided new and unique insight into the characterization and quality of resuscitation of pediatric patients suffering cardiac arrest in a large academic medical center. The results of this three-year study indicate 1) that during an institutional quality improvement initiative, resuscitation performance in terms of chest compression depth, rate and fraction improved, 2) use of raw data from a defibrillator equipped with an accelerometer based sensor in conjunction with custom developed software was used to create otherwise unavailable metrics to analyze resuscitation quality both across the study period and comparatively between groups experiencing acute survival or not and those that did not, and 3) common performance measures of quality may be less strictly influential in terms of acute survival, compared to the number and duration of interruptions to CPR as revealed through both unadjusted comparative analyses and multivariable logistic regression.

During the study period a resuscitation quality improvement program was initiated in the children's center. The focus of this program was to identify every pediatric cardiac arrest that took place in the hospital and to debrief each of these events on a weekly basis using as much objective performance data as possible. The source of data was the ZOLL R Series defibrillator. Data from the events were collected and reviewed using the manufacturer available metrics and then processed using custom software developed by the QI team to quantify additional aspects of performance not readily available "out of the box" from ZOLL. The quality of CPR metrics presented in Table 3 and Table 5 represent many of the metrics this new software produced. The focus of the custom software output was to provide timely and standardized objective data in the form of a report card with visualizations of performance data, to providers who participated in the resuscitation itself as well as anyone in attendance to this "open-door" standing meeting and to use the data as a framework for understanding what aspects went well so as to replicate in the future and what didn't in order to develop strategies to overcome potential performance barriers in the future.

In evaluating performance over the period in which this QI project was underway, the common measures of average depth, average rate, and chest compression fraction would not have statistically significant progress over time. Not until we were able to evaluate individual compressions for depth and rate compliance as well as individual epoch compliance for depth, rate and chest compression fraction were we able detect improvements, with epochs compliant for rate, chest compression fraction and the combination of depth, rate, and chest compression fraction (D+R+CCF) all increasing significantly over the period (RATE: 2013: 33%, 2015 78%; p=0.000 | CCF: 2013: 72%, 2015: 84%; p=0.005; D+R+CCF: 2013:22%, 2015:43%; p=0.000) and percent of chest compressions compliant for rate improving as well (RATE: 2013: 14%, 2015: 82%; p=0.015). These metrics also provided benchmark process measurements with which to assess ongoing progress. Similarly, processing the ZOLL raw data allowed for detailed characterization of interruptions. Prior to the availability of interruption data, the only available metric that could provide some insight regarding interruption time was the chest compression fraction. However, the chest compression fraction is limited in that the number and duration of interruptions are collapsed into the measure. Although both the median number of interruptions and the median number of interruptions greater than 10 seconds didn't decrease over the time period, understanding the frequency and range of interruption duration provided valuable information. Chest compression fraction of 74% and 29 interruptions greater than 10s is different than a chest compression fraction of 74% and 0 interruptions greater than 10s. This insight into interruption duration was particularly important in both building awareness for monitoring long interruption times during CPR. To date, reductions in interruption duration, related directly to survival have been primarily focused toward pre-shock and its association with shock success based on Edelson's work. (Edelson 2008).

The overall unadjusted probability of acute survival was 70% which is less than that of the entire of population experience for arrest in the Children's Center for the period which was 75% (237/316). This may reflect a difference in the type of patients for which the defibrillator was not used. As such, these findings must be considered in the context of patients for which the defibrillator was obtained and the accelerometer placed.

In our multivariable logistic model, it was surprising that depth and rate were not associated with acute survival. These measures are often the primary focus of resuscitation performance reviews and reports of CPR quality in the literature (Chapter 2). They receive emphasis via professional organization guidelines in addition to being reported in simulation and human studies of performance during resuscitation. The present results should not be interpreted to mean that depth or rate are not important factors related to survival, as it is physiologically evident that chest compression force at some minimum level is necessary to generate perfusion pressures for the heart and brain, which are necessary for cellular metabolism and ultimately cardiac and neurologic function. What these results do reveal is that actual depth and rate performance, regardless of the metric used, in all resuscitation events is compliant *most* of the time, despite acute survival outcome. This is somewhat counter intuitive as it would stand to reason that non-guideline compliant chest compression depth and rate performance would be associated with worse outcomes. Providers have been trained to the guidelines for depth and rate, the availability of real-time feedback from the ZOLL defibrillator and team members helping to coach performance during events focus the chest compressor to "aim" for the standard, and these data are reviewed weekly as part of the QI debriefing. Given these factors, it is not surprising the quality of chest compressions seldom falls outside the established guidelines. Performance for depth in the less than one-year olds is a good example: the median values were not statistically significantly different, by survival. However, the IQR for the acute non-survivors was completely within the standard for age as opposed to the IQR for survivors (ACUTE SURVIVAL**+** 1.6 (1.1-1.9), ACUTE SURVIVAL **-** 1.7 (1.5-2.1); p=0.471). This perhaps suggests that as long as depth and rate performance is not *extremely* poor, then other factors may be more influential in terms of survival.

Our findings reveal that one of these, influential factors is the number of interruptions greater than 10 seconds. Interruptions in chest compression can occur for many reasons, some of which are appropriate but too long, as well as inappropriate and either relatively short or long (by definition any inappropriate interruption would be excessively long). Guidelines and consensus statements provide direction regarding overall interruption duration by way of chest compression fraction targets (whose numerators are driven by interruption duration). However, an understanding of "interruption modes" is necessary. Teamwork and communication, procedural interventions, perceived change in patient anatomy and physiology, and the resuscitation environment all play a role in the onset interruptions, their duration and ultimately the growth or restriction of the total count during an event. A next step in developing interruption-related quality metrics should be to incorporate these factors into models which can account for type and appropriateness of interruption along with duration and number as has been done in the present analysis.

This model also has revealed variables that are would appear to be surrogates for severity of illness, such as whether or not the patient was in the ICU, number of previous cardiac arrest events, and patient weight, were not associated with the odds of survival. This information may be particularly useful for providers when making decisions and setting expectations regarding perceived likelihood of survival, determination of effort futility, and overall resuscitation strategy. Anecdotal experience of the QI group suggested the investigation of initial rhythm. In both unadjusted, and adjusted analyses, cardiac arrest events with initial rhythm of bradycardia were associated with return of spontaneous circulation (OR 11.9; CI 1.3, 116.0, p=0.033). The literature and registry-based studies often do not include bradycardic events in comparison with other initial rhythm types (ASYSTOLE, PEA, VF/VT). This work provides additional knowledge in that regard, while also suggesting that more research is needed in understanding factors associated with non-survival of bradycardic cardiac arrest; in this study 11% (n=2 children) of bradycardic cardiac arrest event patients did not survive the event.

CONCLUSION

Over a three-year period during which a pediatric resuscitation quality improvement program was ongoing, evaluation of 1,625 sixty-second epochs revealed improvements in CPR chest compression and interruption-related quality measures. Using raw data from our institutional defibrillators we were able to create higher resolution quality performance variables than were commercially available from the manufacturer. Using these data, we were able to more extensively characterize resuscitation performance over the period as well as compare IHCA event patients who survived their event to those who did not, using both unadjusted and multivariable logistic regression methods. Although chest compression depth and rate are undoubtedly crucial factors influencing survival, in populations where the performance of both is relatively high and variability limited, interruptions to chest compressions become significantly associated with acute survival with a 47% reduction in the odds of survival occurring for every interruption greater than 10 seconds. Further work is needed to understand these interruption modes, the factors that influence them and strategies for their elimination when inappropriate and maximum reduction when absolutely necessary.

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CHAPTER 5
IMPLICATIONS FOR PRACTICE AND POLICY

This work revealed variability in how resuscitation quality is defined, measured, and analyzed. By leveraging hospital information technology and medical device data, identification of pediatric cardiac arrest can be improved with an associated increased capture in the proportion of objective quality data used by QI efforts. Lastly, it demonstrated that resuscitation performance over time can be improved and evaluation of performance using novel methods provides previously unobtainable insight regarding factors that influence survival.

These results show that resuscitation quality can be defined and measured in a myriad of ways and this understanding can focus QI initiatives in novel ways. These initial findings suggest there is tremendous opportunity, in further exploration of device-derived resuscitation quality data, performance patterns, and patient characteristics and their interactions, to drive precision-medicine interventions during pediatric cardiac arrest. The following discussion centers on how these findings can inform practice and policy at the local and national health system level.

PRACTICE

Although further research needs to be conducted in order to understand the generalizability these findings, they still hold potential to inform and influence clinical practice not only at the Johns Hopkins Children's Center but at all medical centers where resuscitation of the pediatric cardiac arrest victims is attempted. The in-depth review of resuscitation quality assessment techniques and metrics described in the first paper, along with the creation of new measures using raw data from smart defibrillators described in the third paper, provide a rich selection of measures for use in numerous ways by providers, analysts, and educators. Use of these measures during event debriefing provides focusing on performance, teamwork, and communication in an objective, structured, and consistent format over time. Perhaps more importantly, it provides the ability to describe resuscitation performance in detail that far exceeds an average summary of one or two measures. Examining what went well or what went poorly in numerous ways and using multiple metrics, increases the potential for insight and improvement. Structured debriefing on objective measures helps to develop a shared mental model of resuscitation quality that providers can use to frame their performance when 1) reviewing events, 2) reviewing new events compared to past events, and 3)entering a patient's room because the code blue button has been pressed.

The second paper describes in great detail the leveraging of a health system's IT infrastructure to create an efficient and reliable system for detecting clinical events, identifying cardiac arrest, and initiating processes for capturing patient physiology and resuscitation quality data. This system is already in place for the Johns Hopkins Children's Center but was designed to be scaled up to accommodate an entire health care organization. The potential exists for this system to be used as the model, if not the system itself, for a unified resuscitation surveillance and quality assessment approach for the entire Johns Hopkins Health System. Currently, the design of this system allows for the tracking of events and can serve as a control mechanism for crucial processes such as the capture and collection of event data. This information can be valuable to departmental directors, unit managers, and safety programs in understanding how cardiac arrest impacts resource allocation and unit stress, while providing live-time data-driven insight that can be used to identify trends in frequency, location, and temporality of event occurrence.

POLICY

At an organizational level, this work provides a set of structure, process, and outcome measures that can be used to drive an organization's cardiopulmonary resuscitation policy regarding performance expectations during a resuscitation and the metrics and analytical approaches to be used during post-event debriefing. This institution's CPR policy does not mandate post-resuscitation debriefing nor does it recommend use of quality measures despite evidence to suggest that objective debriefing post-event is one of the few actions that can drive future performance; perhaps this work can help to bring about such a mandate. At the national level the Institute of Medicine's unifying framework for improving patient outcomes from cardiac arrest, specifies several areas in need of refinement or expansion that this work can help to inform. Of particular relevance is the call to action for development of a national surveillance system based upon a "secure, integrated, data repository for cardiac arrest" (Graham 2015) and the novel approaches to transforming raw data into new measures is relevant to specific aims regarding resuscitation research and continuous quality improvement. Lastly the IOM calls for increased accountability and transparency surrounding cardiac arrest and resuscitation, stating it "can increase operational effectiveness and efficiency by building trust among stakeholders, engaging individuals, and organizations in continuous quality activities, and fostering innovation" (Graham 2015), continuing on to state that the resuscitation field lacks appropriate transparency and accountability for cardiac arrest incidence and outcomes. This work can impact policy decisions not only for Johns Hopkins but others across the nation by setting an example of accountability and transparency. This work provides an approach to understanding resuscitation quality measurement, implementing a surveillance system and collection of objective performance data and, ultimately, sharing analyses of the largest single center resuscitation quality and acute survival outcomes dataset to date.

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BIOGRAPHICAL STATEMENT

Jordan Duval-Arnould was born in Cincinnati, Ohio and is on the faculty of the Johns Hopkins University School of Medicine. His primary appointment is in the Department of Anesthesiology and Critical Care Medicine, and he holds a joint-appointment in the Division of Health Sciences Informatics. He serves on the hospital-wide and pediatric CPR committees and is the Director of Research and Innovation within the Johns Hopkins Medicine Simulation Center.

Jordan is driven to advance pediatric resuscitation science. He has co-authored scholarly works centered on resuscitation, technology, and simulation-based research and training, and has presented his work both nationally and internationally. He has been involved in several multi-institutional endeavors to identify how technology can be used to increase research efficiency and reliability. He is extremely interested in and involved with patient safety and quality initiatives at the Johns Hopkins Hospital and at an international level, particularly in his volunteer capacity as Co-Chair of the Research Committee for the International Pediatric Simulation Society, as well as a Co-Investigator on the Quality of Pediatric Resuscitation in a Multicenter Collaborative (pediRES-Q) research initiative.

Jordan is involved in research, education, and training in the Pediatric Intensive Care Unit (PICU). He is a co-investigator on multiple IRB-approved multidisciplinary research studies. These initiatives join faculty from the PICU with those from across Johns Hopkins who are focused on making developing methods and discovery that will ultimately improve the quality of care provided to our pediatric patients. He co-directs a weekly pediatric resuscitation quality improvement program. This group's mission since January 2013 has been to identify every pediatric cardiac arrest in the Children's Center, collect and analyze objective performance data, and discuss, weekly, every resuscitation in a multidisciplinary peer-to-peer forum. As an educator, Jordan is involved with ongoing resuscitation training and education of providers and staff across the Johns Hopkins Health System.

Jordan graduated from Watkins Mill High School in Gaithersburg, Maryland in 1995, received a bachelor's degree from The Ohio University, School of Telecommunications, in 1999, successfully completed the Emergency Medical Technician-B certification from the City Colleges of Chicago in 2006, and earned a Master's in Public Health from the Johns Hopkins University School of Public Health in 2009. Jordan also has had advanced training and experience in informatics, epidemiology, biostatistics, and medical simulation. At the beginning of his doctoral education from 2010 to 2012 he completed two training fellowships as a National Library of Medicine Informatics fellow, as well as a Johns Hopkins Medicine Simulation fellow.